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Evaluation of Ramp Metering Impacts on Air Quality: The Atlanta I-75 Case Study

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ABSTRACT

Many metropolitan areas use ramp meters as an effective means to reduce freeway congestion. Smoothing the entry of vehicles onto the freeway reduces the potential for traffic flow breakdown and prevents, or delays, the onset of low-speed congested flow conditions. Only five ramp meters have been installed to date in the Atlanta region. Given the limited deployment of ramp meters in Atlanta, GDOT is currently examining the potential benefits of expanding the use of ramp meters in the region to increase system efficiency. However, Atlanta is a non-attainment area for ozone and the air quality impacts of ramp meter operation are uncertain. Previous emissions analyses on metering impacts have been limited by poor quality vehicle activity data and emission rate models that were never designed to examine the impacts of changes in vehicle operating characteristics on emissions. The objectives of this research effort were to: 1) analyze the congestion benefits of the existing ramp meter system, 2) quantify the emissions impacts of ramp operations along the current metered corridor using a traditional emission rate model and an advanced modal emission rate model, 3) use CORSIM to simulate the potential impacts of metering on the corridor under conditions not observed in the field, 4) assess the potential emissions impacts from the simulations, and 5) provide recommendations on the applicability of the research results to future ramp metering strategies that may be proposed in Atlanta.

The research team concluded that transportation planners and engineers should be cautious in the implementation of ramp metering from an air quality perspective. For the corridor-specific scenarios examined in this research, NOx emissions tended to increase under metered conditions. Congestion benefits from metering were predicted to be significant on this corridor for high volume and lane-closure conditions, increasing the potential congestion benefits of metering. Yet, NOx emissions for these scenarios were also projected to increase over non-metered conditions. Given the low congestion levels on the study corridor, and the poor performance of the simulation model under some modeled scenarios, the modeling results for the study corridor are not directly transferable to many other freeway corridors in Atlanta. Hence, despite the findings for this corridor, the research team believes that ramp metering implementation can provide emissions benefits on some of Atlanta's most congested freeway corridors, where flow breakdown is significant. Additional simulation model improvements will be required in order to make this demonstration in future research.

EXECUTIVE SUMMARY

The Georgia Department of Transportation (GDOT) is currently examining the potential benefits of expanding the use of ramp meters in the Atlanta region as a means to improve system efficiency. However, because Atlanta is a non-attainment area for ozone, GDOT desired to evaluate the potential emissions impacts of ramp meter operations. The Georgia Institute of Technology research team proposed to conduct an analysis of the emissions impacts of ramp metering along the existing metered I-75 corridor. The objectives of this research effort were to: 1) analyze the congestion benefits of the existing ramp meter system, 2) quantify the emissions impacts of ramp operation along the current metered corridor using a traditional emission rate model and an advanced modal emission rate model, 3) simulate the potential impacts of metering on the corridor for conditions not observed in the field, 4) assess the potential emissions impacts of the simulations scenarios, and 5) provide recommendations on the applicability of the research results to future ramp metering strategies that may be proposed in Atlanta. The research team collected eighteen days of vehicle activity data along the I-75 five-ramp system just north of the downtown. Researchers collected traffic volumes and speed/acceleration data using laser guns, video cameras, and probe vehicles during the evening peak period when ramps are normally in operation on the corridor. Meters were turned off on four of the eighteen days, allowing the research team to observe the impacts of metering. Researchers used the MOBILE5b and MEASURE Aggregate Modal Model to predict the emission rates from light-duty vehicle activity under the operating mode conditions observed in the field. These emission rates were applied to observed and simulated vehicle activity estimates to predict mass emissions and provide a basis for scenario comparison.

Field observations indicated that the operation of the ramp meters on this corridor provided only a very small decrease in mainline freeway travel time. Given the current low levels of congestion on the study corridor, due to an upstream bottleneck, the operation of the meters did not provide significant congestion reduction benefits. However, the changes in vehicle operations on the ramps and the mainline segments did impact predicted emissions. The predicted changes in onramp hydrocarbon emissions, associated with hard acceleration activity, were significant. Yet, the changes in mass emissions on the ramps were small compared to the predicted emissions changes on the mainline. Total predicted system-wide HC emissions were lower by about 1% on a typical day when the ramp meters were in operation (the combined effect of the 30% to 46% increase in ramp emissions and 2% decrease in mainline emissions). However, the emissions estimates showed an increase in mainline NOx emissions of approximately 4% under metered conditions. System wide NOx emissions were also predicted to increase by approximately 4% because the decrease in NOx emissions at each ramp was insignificant compared to the mainline emissions increase.

Using the field data, the researchers developed and calibrated a CORSIM simulation model application for the metered corridor. The model was used to simulate the effect of ramp metering under various operating conditions. The research team first simulated the observed conditions and then simulated conditions that were never observed on the metered system to examine: 1) the potential effects of high traffic flow conditions as might occur just prior to forced flow breakdown, and 2) the potential effects of a lane-closure where simulated forced flow conditions are achieved. Performing these analyses allowed the team to assess the metered system under a wider range of traffic conditions, providing a better understanding of potential emissions impacts. Simulation model results confirmed the results of other research reported in the research literature; metering can significantly reduce mainline freeway travel times by inducing a slight delay on the ramps and smoothing the entry of traffic onto the freeway. However, under metered conditions on this study corridor, the mainline gram/second emission rates increased at a faster rate than the rate of travel times declined. Thus, high volume simulations lead to potentially higher mainline freeway emissions after metering was introduced. Similarly, metering under peak-hour lane-closure conditions was predicted to increase HC by 4% and NOx by 6% over non-metered lane-closure conditions. It is important to note, however, that the emissions baseline, against which meter-induced emissions changes are compared, is a planning/policy decision. The simulation model predicted that metering under peak-hour lane-closure conditions would increase NOx emissions from approximately 76,600 grams to 81,600 grams. However, the final emissions level remains lower than the peak-hour emissions levels had a lane closure not occurred (87,900 grams). Hence, one can argue that ramp metering under incident and extreme non-recurrent congestion conditions does not constitute an emissions increase from a planning perspective, because the facility emissions remain below those of normal operating levels.

Predicted emissions differences for HC or NOx under metered versus non-metered conditions must be evaluated within a regional context. The daily NOx emissions budget for the Atlanta Region is approximately 245 tons per day (ARC, 1999). The estimated emissions increase due to ramp metering on this study corridor accounts for less than 0.005 to 0.01 percent of the daily regional budget. Even an extensive ramp metering system is not likely to result in large emissions changes relative to the total regional budget.

Predicted changes in speed and acceleration conditions serve as inputs to modal emissions models, which predict emissions as a function of vehicle operating mode. The results of the simulation studies indicated that calibrated CORSIM simulation models require significant improvement before they will accurately simulate the changes in onramp activity profiles. In addition, the CORSIM routines typically underestimated high-speed operations in the downtown corridor. Additional research designed to improve lane change algorithms, car following algorithms, and the interface between the arterial and freeway models should be conducted. Without CORSIM improvement, simulation applications are likely to underestimate emissions under metered and non-metered conditions and may overestimate the percentage increase in emissions likely to result from metering. Notwithstanding the shortcomings of CORSIM speed/acceleration predictions, the high-flow simulation exercises did corroborate research efforts historically demonstrating that ramp metering has a potentially significant impact on mainline average freeway speeds under heavy flow conditions. The lane-closure simulations also supported other research efforts demonstrating that ramp metering has a potentially significant impact on mainline average freeway speeds.

Care must be taken in extrapolating findings from the study corridor simulation modeling results to other freeway corridors. There are no field observations under high-flow or lane-closure simulation conditions to which researchers can compare the simulation results. Given the noted differences between simulated and observed traffic conditions under normal operating conditions, the researchers believe that the simulated flows for high-flow conditions are also likely to underestimate the maximum speeds and acceleration rates on the mainline. Hence, real world emissions under metered conditions for heavy congestion and lane-closures may be higher than predicted by the simulation outputs. Thus, although the percentage emissions increases that result from metering may be somewhat lower than simulated, the net magnitude of the predicted change may be higher.

During the collection of vehicle activity data, the Georgia Tech Air Quality Laboratory performed a concurrent emissions verification study. The Laboratory conducted remote sensing studies, instantaneous infrared measurements across vehicle exhaust plumes to assess the level of emissions from the vehicles, to assess the relative emissions distributions and fraction of high emitting vehicles in the monitored fleet. Researchers also conducted vertical flux experiments to measure vertical movement of pollutants from the roadway. Estimates of vertical pollutant transport were linked back to vehicle activity to quantify the emissions effect of the fleet as a function of onroad vehicle operating conditions. The study concluded that measured emissions above the roadway are highly variable, and heavily influenced by the presence of heavy-duty trucks. The impact of trucks on monitored emissions is so significant that pollutant concentration spikes observed in the field link back to specific video images of trucks passing through the observation site. Researchers also observed significant variation in emissions as a function of the onroad fleet composition, which varied by time of day (especially on ramps).

Based upon emissions flux measurements, the research team determined that emissions under observed congested conditions were lower than under observed free flow conditions. That is, as traffic volumes decline and vehicle speeds increase significantly, air samples collected above the facility demonstrated that emissions from the monitored facility increased. Because emissions are the product of activity and emission rates, field observations support the prediction that emission rates are increasing at a much more rapid rate than traffic volumes are decreasing. Hence, high-speed emissions on freeway are cause for significant emissions concern.

The emissions experiments, however, did not observe a statistically significant difference in emissions under metered and non-metered conditions. In part, this is because predictions were only prepared for light-duty vehicles. The absence of a statistically significant measurable difference for metering is also not surprising because the predicted changes are too small to fall outside of the boundaries of experimental sampling and analysis error (within ±10%). The predicted emission increase for light-duty vehicle HC was only 1% and the predicted increase for light-duty vehicle NOx was only 4% for the mainline sections near the sampling locations. Hence, the sampling effort could neither support nor refute the predicted emissions increase from ramp metering on this system.

As freeway conditions approach breakdown, regions need to decide whether trading an emissions increase for a significant reduction in travel time warrants the implementation of metering strategies. If so, the region will likely need to identify alternative means of reducing the emissions resulting from improved traffic flow on the freeway corridor. Given the small relative contribution of potential metered corridors to the overall regional emissions inventory, and the potential travel time savings of highway users, it seems reasonable to pursue alternatives that compensate for the metered system emissions increase. Simulation modeling tools and modal emissions models can help with these decisions.

The researchers acknowledge that there is a great deal of uncertainty in both the simulation modeling runs and the emission rate model outputs used in the analyses. However, the results of the field and simulation studies indicate that additional research on the emissions impacts of ramp metering is warranted. First, while ramp metering on the I-75 study corridor may never yield emissions benefits, ramp metering in other significantly congested areas may still benefit from metering. The research team recommends similar studies be conducted on the I-75/I-85 connector (to I-20) and on one of the most congested segments of the I-285. These corridors achieve such high levels of congestion that emissions may decline when metering smoothes traffic flow. Any simulation analyses should employ simulated traffic volumes coupled with appropriate speed/acceleration profiles measured from existing systems (until researchers improve the simulation models to provide better estimates of speed/acceleration profiles). Second, MOBILE6 and more advanced second-by-second modal emission rate models will soon replace the models employed in this study. Once the new emission rate models become available, the research team recommends repeating the analyses reported in this study using the observed activity data and the new emission rates.

Ramp metering has been and will likely continue to be a popular cost-effective traffic management tool with a high potential for improving freeway traffic flow. Ultimately the decisions to implement a ramp metering system will be a function of the specific traffic operations and air quality issues associated with the area under consideration. Given the projected emissions increases, optimizing the tradeoff between time savings and increased emissions will likely be next order of business in modeling the detailed impacts of ramp meters.

CHAPTER 1
INTRODUCTION

The Clean Air Act Amendments of 1990 (CAA Amendments) and the Transportation Equity Act for the 21st Century (TEA21) both contain provisions that encourage the use of transportation control measures (TCMs) to help reduce motor vehicle emissions. The primary goal of these provisions is to assist states and regions in complying with the National Ambient Air Quality Standards (NAAQS). The most widely implemented class of TCMs in the United States, in attainment areas and non-attainment alike, is traffic management strategies designed to improve traffic flow. In 1992, 36 percent of the Congestion Mitigation and Air Quality (CMAQ) program funds were obligated to traffic flow improvement projects, second only to transit related projects (FHWA, 1994). Freeway ramp metering is one traffic flow improvement strategy that is gaining popularity in many urban areas throughout the United States.

A rapid increase in vehicle-miles of travel and congestion levels, coupled with limitations on construction of additional lanes to handle increased traffic demand, has increased the importance of ramp metering as a freeway traffic control. Ramp metering is one of the most cost-effective ways to alleviate freeway traffic congestion (Meyer, 1997). Ramp metering controls the flow of traffic onto a freeway and breaks up vehicle platoons (natural fluctuations in entering traffic streams) that impair optimal freeway flows. The balanced entry of vehicles reduces the potential for freeway traffic flow breakdown and thereby significantly reduces overall system delay. Inducing small delays on the onramps can significantly reduce mainline travel time. A system-wide strategy optimizes freeway flow control by controlling entry at numerous ramps to stabilize the flow approaching critical network locations.

In conjunction with installation of the Atlanta Advanced Transportation Management System (ATMS), the Georgia Department of Transportation (GDOT) installed meters on five ramps along the northbound corridor of Interstate 75 in metropolitan Atlanta. The existing ramps were retrofitted with variable interval meters to control flow of traffic onto the freeway mainline. The ramp meters are only located on the northbound direction for five consecutive interchanges, Northside Drive, Howell Mill Road, Moores Mill Road, West Paces Ferry Road, and Mount Paran Road. Each interchange offers a unique geometry that has the potential to affect the vehicle activity of the merging traffic, and impact the response of the vehicles operating along the corridor.

The CAA Amendments and TEA21 encourage the use of traffic flow improvements, such as ramp metering, as a means to improve air quality, because these strategies mitigate traffic congestion. However, emissions from motor vehicles are not in direct proportion to traffic congestion and vehicle delay. Emission rates are a function of delay measures, such as average speed, but also of the modal operation of the vehicle associated with speed/acceleration profile. Thus, it should not be surprising that the current version of the USEPA model (MOBILE5b) does not produce accurate emissions estimates under certain applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). The MOBILE5b mode utilizes speed correction factors to adjust emissions, to account for average speeds that differ from the average speed of the USEPA new vehicle certification testing cycle. However, the FTP drive cycle does not adequately represent the range of driving conditions encountered under most typical driving scenarios. To date, modeling techniques have not been capable of the emissions effects that result from driving conditions that differ significantly from laboratory test conditions. Thus, the models are unable to accurately analyze the air quality impacts of many traffic management strategies, including ramp meters. Modal modeling approaches that take into account the physical operating mode (speed/acceleration conditions) of vehicles are necessary to evaluate the impacts of ramp metering systems.

One research study indicated that the USEPA MOBILE5b model would predict reduced emissions levels resulting from ramp metering systems (Sierra Research, 1997). However, other research has indicated that the MOBILE series of models are inaccurate and tend to under-predict emissions levels under many real world scenarios. Additional research has indicated that when vehicle operating mode is considered, emissions rates for vehicles operating on freeway onramps would possibly increase when ramp meters were in place (Sullivan, 1993). Recent studies also indicate that a disproportionate amount of emissions occur under limited levels of modal activity, such as load induced enrichment, i.e. low air/fuel ratios (LeBlanc, et al., 1994). That is, a large amount of vehicle emissions, particularly carbon monoxide and hydrocarbons, result from small amount of vehicle activity such as might occur under hard acceleration conditions at an onramp. Studies show that roadway grade (an acceleration against gravity) can increase emissions more than tenfold, and that one sharp acceleration may cause as much pollution as the remaining portion of a trip (Cicero-Fernandez and Long, 1995; Kelly et al., 1993). Indeed, vehicle acceleration to freeway speed after stopping at a ramp meter would be a likely scenario for high power demand and enrichment conditions. What is not known, is the extent to which onramp emissions are elevated and what the modal activity and related emissions impact would be for vehicles operating on the freeway mainline. Also, the effect of ramp design factors (i.e. geometric design, grade, acceleration distance) and what mainline flow conditions influence the most significant changes in emissions rates are unknown. The research conducted in this study involved collection of detailed onroad operating mode data for a set of ramp meters and the application of traditional average speed and modal emission rates to analyze these potential emissions tradeoffs.

Over the past several years, the Georgia Institute of Technology has been developing a modal emissions model that associates vehicle emissions with certain types of engine and vehicle modal operation (i.e. cruise, acceleration, deceleration, idle, and power demand) rather than average speed. The Mobile Emissions Assessment System of Urban and Regional Evaluation (MEASURE) modeling framework incorporates MOBILE5 emissions rate relationships as well as an Aggregate Modal Model (Guensler, et al., 1997; Fomunung, et al., 1999). The aggregate modal model is a statistically based model that predicts emissions for various vehicle technology groups as a function of vehicle operating mode distributions. Because the aggregate modal model is sensitive to changes in vehicle operating characteristics expected with the implementation of ramp metering systems, it served as one basis for evaluating the emissions impacts of the Atlanta ramp metering systems.

Given the importance of vehicle operating mode on emissions, it is important to assess how the introduction of ramp meters changes the operations of vehicles on ramps as well as along the mainline freeway segments. The research team collected light-duty vehicle activity data from the onramps and mainline freeway facility along the existing metered system. Video equipment, traffic counters, laser rangefinders, and floating cars equipped with distance measuring instruments were all employed to collect activity and speed/acceleration profiles on the freeway and metered ramps. Resource limitations prevented the collection of local roadway operating mode data. The team collected approximately four hours of data during each of 18 field studies (over a two-month period). Researchers then analyzed the modal operation (speed/acceleration profiles) of the light-duty vehicles along the corridor, and estimated the emissions for the metered ramp and mainline system.

The basic goal of the project was to measure the activity and operating modes of light-duty vehicles on Atlanta's five-ramp metered facility and to analyze system impacts on congestion and motor vehicle emissions. Emissions for measured field activity data were estimated using both the MEASURE Aggregate Modal Model and the Environmental Protection Agency's MOBILE5b emission rate modeling functions. A significant portion of this research included the assessment of how varying mainline congestion levels and flow conditions influenced onramp emission rates. The results of the congestion and air quality analyses were used to identify the design parameters that significantly impact the emissions from the metered system. To achieve the goals of the project, researchers:

- Undertook a basic literature review on impacts of ramp metering on traffic activity and the capabilities of various equipment packages and modeling tools employed
- Developed field deployment methods designed to capture and store comprehensive vehicle activity and operating mode profile data for the existing Atlanta ramp metered facility.
- Collected 18 days of comprehensive, afternoon peak period, vehicle activity data, under metered and non-metered conditions
- Employed MOBILE5b and MEASURE Aggregate Modal Model emissions functions to predict emissions from measured speed/acceleration profiles for merging vehicles, weaving sections, and mainline traffic flow
- Developed the CORSIM base scenario for use in predicting changes in both traffic flow and speed/acceleration profiles for the existing Atlanta ramp-metered facility
- Used the field data to calibrate the CORSIM base scenario for the metered corridor so that the model accurately predicts segment traffic volumes and delays
- Modified the CORSIM model to output vehicle speed/acceleration profiles
- Coupled the CORSIM outputs with MEASURE Aggregate Modal Model emission rates to quantify the potential impact of the Atlanta ramp meter operations on system efficiency and vehicle emissions under observed conditions and high travel demand conditions (when ramp metering provides the greatest congestion benefits)
- Performed field emissions validation tests (remote sensing and vertical emissions flux studies) to compare the results of MOBILE5b and MEASURE Aggregate Modal Model application and to evaluate the observed emissions effects of ramp metering
- Identified the geometric design and ramp timing plan parameters that significantly impact the emissions from the metered system so that the results could be used to develop guidelines for optimizing the air quality benefits of metered systems.

The report organization follows the implementation plan for the project. Chapter 2 provides a discussion of the background of this research including a review of air pollution issues, motor vehicle emissions, and air quality and emissions rate modeling. Chapter 3 presents the general research approach. This includes a discussion of the research hypothesis and objectives, in addition to the proposed experimental design. Chapter 4 provides details of the research procedures; focusing on the data collection process and field deployment, site descriptions, and data analysis methods. The findings from the field assessment of vehicle activity and predicted from the observed activity are presented in Chapter 5. Chapter 6 then summarizes the simulation modeling results (activity and predicted emissions) for the freeway corridor under observed, high flow, and lane closure conditions. In Chapter 7, the Georgia Tech Air Quality Laboratory presents the findings from concurrent remote sensing and vertical emissions flux validation studies. Finally, Chapter 8 includes the research conclusions and final recommendations.

CHAPTER 2
BACKGROUND

In the thirty years since passage of the 1970 Clean Air Act (CAA), metropolitan areas have made great strides in reducing the level of air pollution from automobiles and stationary sources. Despite improvement made by industry, air quality problems still persists today in almost every metropolitan area in the country (174 urban areas in total). Emissions from onroad mobile sources remain one of the primary contributors to the air pollution problem. Despite considerable improvements in vehicle emissions control, mobile sources still account for a significant portion of urban air pollution (USEPA, 1996). Although individual vehicles emit fewer pollutants from the tailpipe with each new model year, total emissions soon begin to rise due to increases in vehicle activity and ownership. With each passing year more vehicles, making more trips, and driving more miles contribute to our current air pollution problem.

The Clean Air Act (CAA) Amendments of 1990 have strengthened the air pollution legislation through more stringent tailpipe standards and rules for metropolitan areas developing transportation and air quality plans. One portion of the legislation encourages the use of transportation control measures (TCMs) as a means to help mitigate air pollution from mobile sources. TCMs are transportation improvements or programs designed to reduce pollution levels through vehicle trip reduction, transportation system efficiency improvement, increased vehicle occupancy, or shifts to non-automobile modes. This includes such strategies as transit improvement, travel demand management, and traffic flow improvements (e.g. ramp metering).

To help encourage the implementation of ramp metering and other TCMs, the U.S. Department of Transportation (USDOT) has included specific funding provisions for TCMs in the last two federal transportation bills. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and the Transportation Equity Act for the 21st Century (TEA-21) both contained provisions for Congestion Mitigation and Air Quality (CMAQ) programs. The CMAQ program specifically sets aside federal transportation funds for air-quality-friendly transportation improvements, such as ramp metering systems. The current legislation, TEA-21, earmarked 8.1 billion dollars for the CMAQ program over the next six years (FHWA, 1999). The question is whether appropriate strategies are being selected, considering the uncertainty in predicting TCM air quality impacts.

2.1 Air Quality Standards and Criteria Pollutants

Under the CAA Amendments of 1990, the U.S. Environmental Protection Agency (USEPA) promulgates air pollution standards for six criteria pollutants: oxides of nitrogen (NOx), oxides of sulfur (SOx), carbon monoxide (CO), particulate matter smaller than 2.5 microns (PM), lead (Pb), and tropospheric ozone (O_3). The intent of the National Ambient Air Quality Standards (NAAQS) is to protect public health and welfare. The NAAQS establish a primary and secondary standard for most of the six criteria pollutants. In 1995, approximately 80 million people in the United States lived in areas that did not meet at least one of the NAAQS (USEPA, 1996). Under the CAA Amendments, the USEPA is required to review and update the NAAQS every five years. Table 2-1 provides the current NAAQS.

Table 2-1
NAAQS Primary and Secondary Standards (40 CFR 50)

Pollutant	Primary		Secondary	
	Type of Average	Standard	Type of Average	Standard
CO	8-hour	9 ppm	No secondary standard	
	1-hour	35 ppm	No secondary standard	
Pb	Maximum quarterly average	1.5 μg/m^3	Same as primary standard	
NO_2	Annual arithmetic mean	0.053 μg/m^3	Same as primary standard	
O_3	1-hour average[1]	0.12 ppm	Same as primary standard	
	8-hour average	0.08 ppm	Same as primary standard	
PM-10	Annual arithmetic mean	50 μg/m^3	Same as primary standard	
	24-hour	150 μg/m^3	Same as primary standard	
PM-2.5	Annual arithmetic mean	15 μg/m^3	Same as primary standard	
	24-hour	65 μg/m^3	Same as primary standard	
SO_2	Annual arithmetic mean	0.03 ppm	3-hour	0.5 ppm
	24-hour	0.14 ppm		

[1] Only for areas designated nonattainment before adoption of 8-hour standard in July 1997

The criteria pollutants and issues associated with the ambient standards are described in more detail in Appendix A. The most relevant air quality issues associated with the ramp metering research effort relate to the emissions of pollutants that lead to ozone formation (hydrocarbons and oxides of nitrogen). Ground level ozone is a serious air pollution problem in the Atlanta region.

Unlike the other five criteria pollutants, ozone is not emitted directly into the air. Ozone forms in the atmosphere when NOx compounds and VOCs react with heat and sunlight. The resulting concentration of ozone is a complex function of weather conditions and emissions of ozone precursors (chemical compounds that react to form ozone). NOx compounds are the result of combustion and approximately 50-70 percent of NOx emissions result from mobile sources. Volatile Organic Compounds (VOCs) are reactive hydrocarbons that contribute to O_3 formation. VOC emissions result from combustion as well as evaporation of fuels and solvents. Although VOCs are not a criteria pollutant (that is, there is no ambient standard for VOCs) they are an important player in the formation of ozone. It is therefore just as important to monitor and control VOC emissions as it is other criteria pollutants. This is particularly important in urban areas where motor vehicles can contribute more than 30 percent of the total VOC emissions. Given the high freeway traffic volumes, transportation sector NOx and VOC emissions are significantly affected by the operating characteristics of the freeway system.

2.2 Motor Vehicle Emissions

Motor vehicle emissions contribute significantly to four of the six criteria pollutants, CO, NO_2, PM, and O_3. Of these four pollutants, motor vehicle emissions compose significant portion of emissions, 70-90 percent of CO emissions, 30-50 percent of NO_2 emissions, and at least 15 percent of PM. In addition to hydrocarbon emissions from vehicle refueling and evaporation, motor vehicles emit unburned or partially burned hydrocarbons from combustion. In an effort to control vehicle emissions, the CAA Amendments require that new vehicles meet tailpipe emissions standards established by the USEPA. Automobile manufacturers are required to control the emissions of VOCs, CO, NOx, and PM. Manufacturers are also responsible for developing emissions control systems that are durable for the full life of a vehicle. That is, the USEPA has established standards for new vehicles and onroad vehicles, at 50,000 and 100,000 accumulated miles (USEPA, 1998). New vehicle exhaust emissions standards (certification standards) are based on the Federal Test Procedure (FTP) driving cycle and measured in grams per mile for hydrocarbons and each of the criteria pollutants.

Tailpipe standards have contributed significantly to the reduction of motor vehicle pollution. Since the introduction of tailpipe standards in 1970, per mile vehicle emissions have declined 69 percent for CO, 53 percent for NOx, 78 percent for VOCs, and 69 percent for PM10 (Davis, 1997). In addition, the CAA Amendments also contain provisions to reduce motor vehicle related emissions through vehicle inspection and maintenance (IM) programs for in-use vehicles to ensure that they maintain acceptable emissions levels.

Despite this, onroad emissions remain a serious problem due to the increase in vehicle travel. From 1970 to 1995, the vehicle miles of travel (VMT) in the U.S. increased by 118 percent. Yet, new vehicles are 70% to 90% cleaner than they were 30 years ago. Although significant reductions remain available through continued technological improvement, long-term mobile source emissions reductions may need to come from changes in travel behavior and activity as well as other changes in vehicle technology. This research focuses on VOCs and two criteria pollutants, CO and NOx, from motor vehicles and control of these emissions from metered freeway systems. Particulate matter is also of great concern due to its health impacts and emissions uncertainty. However, the science of modeling mobile source particulate emissions is still lacking, so PM analyses have not been included in the report.

2.2.1 Combustion

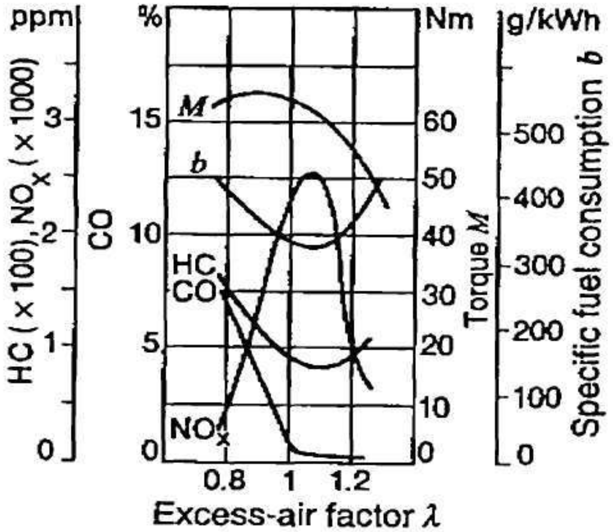
The internal combustion engine seems likely to remain the primary means for powering motor transportation for the near term, as it has been for the last 100 years. Combustion is the process of converting chemical energy into mechanical energy or force that is used to power transportation vehicles. The basic combustion process consists of the oxidation of a fuel in an enclosed space to create heat, pressure, and combustion byproducts. The majority of highway vehicles utilize gasoline as the combustion fuel, although diesel fuel is also used for a significant portion of the total fleet, particularly heavy trucks. This notwithstanding, gasoline is still the primary fuel for light-duty vehicles (LDV). Therefore, the following discussion focuses on the emissions impacts of gasoline spark ignition (SI) engines.

Ambient air used in the combustion process is composed of approximately 20 percent oxygen and 79 percent nitrogen. NOx forms in the engine cylinders under the high pressure and temperature conditions of combustion. Temperature and pressure conditions drive the rate and magnitude of NOx exhaust formation. If the combustion process is not carried to completion, CO and hydrocarbon (HC) emissions result. That is, if the CO is not be fully oxidized to CO_2 and not all of the fuel is consumed, CO and HC emissions are produced. Complete combustion is favored by excess air and high temperatures, which reduces CO and HC emissions, but runs counter to the control of NOx emissions (because NOx formation is a function of peak combustion temperatures and pressures). The critical component in the combustion process affecting the level of motor vehicle emissions is the air/fuel ratio in the combustion chamber (Heywood, 1988).

A balance between the fuel and the air needed to oxidize the fuel during combustion is referred to as stoichiometric combustion. The stoichiometric air:fuel ratio by mass for most spark ignition engines is around 14.7:1. The optimum air/fuel ratio is a trade off between efficiency, optimum power, and pollution formation. If the engine has a need for increased power for acceleration or to climb a hill, more fuel can be introduced into the cylinder to improve power output. Under these conditions and the air/fuel mix runs rich (heavy in fuel). Under enrichment conditions, there is not enough oxygen present to chemically convert the HC in the gasoline to CO_2 and H_2O. Hence, CO and unburned HC increase dramatically under enrichment conditions. Figure 2-1 shows the relationship between air:fuel ratio, torque output, and fuel consumption. Torque "M" (and power output) is maximized when the air/fuel ratio is slightly rich, while the brake-specific fuel consumption "b" is minimized (better fuel economy) when the air/fuel ratio is slightly lean (Bosh, 1996).

Engine-out NOx emissions concentrations are highest just lean of stoichiometric levels. If the air/fuel ratio becomes too lean, combustion efficiency drops and eventually engine misfire occurs (leading to low NOx emissions and high concentrations of CO and HC). An engine operating slightly lean yields low CO and HC concentrations until the mixture becomes excessively lean and combustion efficiency drops. CO and HC emissions increase as the air/fuel ratio becomes richer. NOx levels are low under rich mixtures due to lower peak combustion temperatures and insufficient oxygen present to form NO and NO_2. In addition, under cold operation when a vehicle is first started and the fuel vaporization level is low, the fuel flow is increased to provide an easily combustible rich air/fuel mix. The inefficient combustion that occurs during such cold mode operation also results in elevated CO and HC concentrations. The critical factor is that air/fuel ratios that result in lower levels of CO and HC concentrations run counter to the level of NOx concentrations (Heywood, 1988).

Figure 2-1
Power Output, Emissions, Fuel Consumption, and Air/Fuel Relationship



Rich Lean

Source: Bosch, 1996

When increased concentrations of NOx, CO, and HC are present in the combustion chamber after the ignition stroke, these compounds become part of the combustion exhaust and exit as tailpipe pollutants. The low air/fuel ratio conditions that result in these pollutants, particularly CO and HC, only occur during a small portion of activity that comprises a typical vehicle trip. Fuel rich combustion mixtures occur during high power demand activity such as during rapid acceleration or grade climbing, and negative power demand, such as during deceleration activity (Kelly and Grolicki, 1993; Cicero-Fernandez, et al., 1997). During the majority of a typical trip, a vehicle engine is warm and operation at gradual acceleration and deceleration rates or cruising at a constant speed. The length of a trip, the type of road traveled (e.g. arterial or freeway), and the congestion level all contribute to the percent of a given trip spent under enrichment conditions.

Exhaust gas after treatment consists of the use of catalytic converters to reduce CO, HC, and NOx tailpipe emissions. There are two types of catalytic converters found in vehicles in the current fleet. They consist of the oxidation catalyst and oxidation/reduction catalyst, also known as the three-way catalyst. In an oxidation catalytic converter, the exhaust gas passes through a substrate in the exhaust system that is coated with small amounts of an active catalyst (e.g. noble metals such as platinum (Pt) and palladium (Pd)). In a high temperature environment, these metals oxidize the HC and CO compounds in the exhaust. The high temperature requirements mean that emissions control is negligible during cold engine start conditions. Three-way catalytic converters promote oxidation of partially burned compounds, but simultaneously reduce the NOx exhaust gases to N_2 and O_2. It should be noted that the catalytic converter performance is optimized during stoichiometric combustion with an air fuel ratio of 14.7:1. If the mix is rich, the conversion of CO and HC is reduced, while a lean mix limits the reduction of NOx (Guensler, 2000). Thus, engine computers strive to maintain stoichiometric combustion.

The past 10 years have brought more advancement in engine technology than the previous 90 years. With the innovation of: 1) lightweight materials, 2) synthetic lubricants, and 3) onboard computer controls, today's automotive manufactures can produce engines with better performance, emissions control, and fuel economy than in years past (Guensler, 2000). The computer controls that oversee the air:fuel ratios significantly impact the emissions from vehicles under a variety of onroad operating conditions. This computer control system is the direct link between vehicle operation and air:fuel ratio. On modern vehicles, onboard engine and environmental sensors are linked to a computer program that determines the air:fuel ratio as a function of engine and vehicle operations.

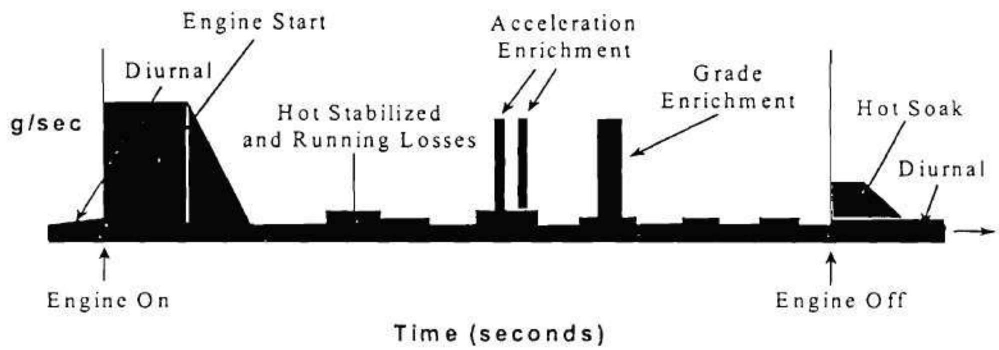
Onboard computer engine control and diagnostics are the final emissions control technology found in today's motor vehicles. Modern vehicles are equipped with numerous sensors and actuators that are under computer or electronic control. These systems monitor and adjust numerous engine operating parameters that are important to the level of exhaust emissions. For example, ignition timing, fuel injection, engine temperature, exhaust oxygen concentration, air/fuel ratio, and manifold pressure are all precisely controlled by computer systems in a modern vehicle. As a result, the engine is able to operate more efficiently and operate in enriched modes less frequently, even under high levels of power demands (Guensler, 2000). Despite these controls, motor vehicles still account for a large portion of air pollution in urban areas. It is important to understand the characteristics of motor activity that override emissions control and lead to rich air/fuel mixtures and potentially elevated emissions levels.

2.2.2 Vehicle Acceleration and Power Demand

The power or torque available at the drive wheels produces the motive force needed to overcome resistance and allow a vehicle to accelerate. Because power at the drive wheels is derived from the engine any time the vehicle accelerates a load is placed on the engine. The engine load for typical vehicle is a function of the speed of the vehicle, change in speed, accessory scavenge (e.g. air conditioning or fan), and load on the vehicle (e.g. towing or grade). When power demands are in a normal range, the engine operates near stoichiometric. When excessive power demands are placed on the engine, the air/fuel ratio 'goes rich' and increased CO and HC emissions will result along with lower fuel economy. An engine in a typical passenger vehicle has enough power available to accelerate at 3-5 mph/s^2 at low speeds without leading to enriched air/fuel conditions (Newton, et al, 1996). At higher speeds, the available power declines as power is consumed to overcome wind resistance. Therefore, power demand for acceleration rates higher than those listed above results in enrichment. Rich air/fuel mixtures are often produced as a direct result of how the emissions control system is programmed. Automobile manufactures allow for rich operations under certain conditions to provide for better performance and protection of engine parts (Guensler, 2000).

As discussed earlier, power demand enrichment leads to both higher combustion-out emissions as well as reduced catalytic converter control system efficiency. The levels of HC and CO emissions can increase by two orders of magnitude for brief periods under these conditions. As a result the vehicle emissions associated with a given trip can vary greatly depending on the level and frequency of the power demand and other vehicle technology, fuel and environmental parameters. Figure 2-2 illustrates the emissions of HC emissions over time as an engine is started and run during a typical onroad trip (Bachman, et al., 1996). Evaporative emissions are shown on the far left of the chart associated with diurnal temperature fluctuations. When the engine is started, emissions are high during the period of time required for the catalyst o warm up and combustion to stabilize. Emissions drop significantly, becoming a function of engine speed under normal low-power conditions. However, the chart illustrates that high power demand conditions, such as a hard acceleration or acceleration up a grade, result in significant bursts of tailpipe emissions as the fuel mixture goes rich. Finally, after the engine is turned off, the evaporation of hydrocarbons (the fuel) continues at a higher rate until the engine cools down.

Figure 2-2
HC Emissions from a Hypothetical Vehicle Trip



Source: Bachman, et al., 1996

Despite the numerous advancements in automobile engine technology, the continued growth in travel motor vehicle related pollution remains as a serious urban air quality concern. Consequently, the CAA Amendments require continued efforts to the reduction of air pollution from the transportation sector or mobile sources. Areas that do not meet the NAAQS must develop air quality management plans that include the monitoring and control of motor vehicle emissions to the extent that the State determines are necessary to achieve the NAAQS.

2.3 Air Quality Planning

Vehicle emissions certification standards have resulted in great strides in the reduction of motor vehicle exhaust emissions. Vehicles manufactured today are in the order of 70-90 percent cleaner than they were 30 years ago, but motor vehicles still contribute significantly to air pollution problems. Therefore, the CAA Amendments require additional counter-measures and plans to reduce motor vehicle emissions, particularly in areas with existing air quality problems. Regions with air quality problems implement these requirements in their State Implementation Plans (SIPs).

The SIP is a blueprint developed by a given state environmental quality division for outlining their process for reaching and maintaining attainment of the NAAQS. The SIP, which must be approved by the USEPA, identifies specific actions and programs to be undertaken to control emissions within the nonattainment boundary. The plan consists of a monitoring and inventory process for emissions from all sources (stationary, area, indirect, and mobile). Emissions control programs for stationary sources, such as power plants and manufacturing factories, are outlined in the CAA Amendments as specific rules and regulations. Apart from the tailpipe emissions certification standards, the control of motor vehicle emissions is less defined. Under the SIP requirements, the state must demonstrate reasonable progress toward achieving the NAAQS and be within their allowable emissions budget under the predetermined timeline. Mobile source emissions play a major role in this process. Part of the demonstration includes how the emissions from motor vehicles declines over time. In addition, there are several requirements in the regulations that call for the monitoring of mobile source emissions. The primary condition within the CAA Amendments for mobile source emissions is that transportation plans developed by metropolitan planning organizations (MPOs) in nonattainment areas must conform with the SIP (USEPA, 1995).

As part of the SIP development process, the state determines a mobile source portion of the total nonattainment area emissions budget, based on the federal motor vehicle control plan. Typically, this budget shrinks as the plan emissions reduction requirements take effect in future years. Most of the mobile source emissions reductions are achieved through the influx of newer and cleaner vehicles in the fleet. The conformity process insures that the efforts of the state and the expectations of the SIP are not compromised through increased vehicle travel induced by transportation plans at the metropolitan level. If the emissions estimates from the implementation of certain transportation plans do not conform with the emissions budget milestones set in the SIP, then the plans cannot be adopted for implementation and projects in the plan can not be built. In such a case, the transportation plan must be revisited and developed in such a way that it conforms to the SIP. The CAA Amendments contain provisions for areas to offset motor vehicle related emissions through the use of Transportation Control Measures.

Transportation control measures (TCMs) are intended to mitigate mobile source air pollution. TCMs are transportation improvements or programs with the intended result of a decrease in pollution levels through vehicle trip reductions, transportation system efficiency improvement, vehicle inspection programs, higher vehicle occupancy, mode shift to transit, or the use of less polluting alternative fuels. The specific TCMs that are included in the CAA Amendments and outlined in Section 108(f)(1)(A) of the 1990 Amendments are as follows:

(i) programs for improved public transit;

(ii) restriction of certain roads or lanes to, or construction of such roads or lanes for use by, passenger buses or high-occupancy vehicles (HOVs);

(iii) employee-based transportation management plans, including incentives;

(iv) trip reduction ordinances;

(v) traffic flow improvement programs that achieve emissions reductions;

(vi) fringe and transportation corridor parking facilities serving multiple-occupancy programs or transit service;

(vii) programs to limit or restrict vehicle use in downtown areas or other areas of emissions concentration, particularly during periods of peak use;

(viii) programs for the provision of all forms of high-occupancy, shared-ride services;

(ix) programs to limit portions of road surface or certain sections of the metropolitan area to the use of non-motorized vehicles or pedestrian use, both as to time and place;

(x) programs for secure bicycle storage facilities and other facilities, including bicycle lanes, for the convenience and protection of bicyclists, in both public and private areas;

(xi) programs to control extended idling of vehicles;

(xii) reducing emissions from extreme cold-start conditions;

(xiii) employer-sponsored programs to permit flexible work schedules;

(xiv) programs and ordinances to facilitate non-automobile travel, provisions and utilization of mass transit, and to generally reduce the need for single-occupant vehicle travel, as part of transportation planning and development efforts of locality, including programs and ordinances applicable to new shopping centers, special events, and other centers of vehicle activity;

(xv) programs for new construction and major reconstruction of paths, tracks or areas solely for the use by pedestrians or other non-motorized means of transportation when economically feasible and in the public interest. For purposes of this clause, the Administrator shall also consult with the Secretary of the Interior;

(xvi) programs to encourage the removal of pre-1980 vehicles.

This list includes wide range of transportation improvements and programs intended to provide flexibility to transportation and air quality planners. However, many TCMs designed to reduce congestion have unknown effects on emissions. Legislation requires that all TCM projects demonstrate an emissions reduction, but the demonstration process is often crude and imprecise (Crawford, et al, 1995). One area that has generated controversy is the fifth TCM on the CAA Amendment list above; traffic flow improvement programs that achieve emissions reductions.

With increasing limitations on available right-of-way and financial resources for new road construction, focus transportation agencies have been focusing on managing the existing transportation system more efficiently. This is particularly true in urban areas where congestion problems are the worst and land values are high. One of the most common forms of transportation management is the wide variety of traffic flow improvements (ITE, 1992). The concept behind these improvements and transportation management strategies in general is to improve the efficiency of the existing transportation system through a better utilization of the present infrastructure. Traffic flow improvements focus on freeway and arterial traffic congestion and strategies that optimize capacity and throughput. Almost every major urban area in the United States is experiencing increases in congestion levels (FHWA, 1996). According to the Texas Transportation Institute, during the period from 1982 to 1996, congestion levels (based on vehicle density, in San Francisco, Denver, and Atlanta), have increased by 32, 27, and 36 percent respectively (TTI, 1998). Although the methods and metrics employed in the TTI study are hotly debated, sufficient evidence suggests that congestion levels continue to increase in most major urban areas across the country. This has led to the increased popularity of the practice of implementing traffic flow improvement projects. Thus, it is becoming increasingly important to understand the air quality impacts of these projects.

Under the basic assumption that traffic flow improvements that are likely to increased average travel speeds also leads to lower vehicle emissions, many such projects are undertaken across the country. As discussed in the previous section, motor vehicle emissions are the result of a complex process related to power demand and not simply the function of average vehicle speed. Due to the fact that the operations impacts of traffic flow improvements are highly variable and difficult to predict accurately, and that the analysis tools used to evaluate the emissions changes are also limited, the true emissions impact of a given project is difficult to estimate (Hartner and Lawlor, 1995). Despite this, traffic flow improvements and related transportation management strategies are the most popular TCMs in U.S. cities. In 1992, 85 of the 183 TCM projects in nonattaniment areas funded through the congestion mitigation and air quality (CMAQ) improvement program were composed of traffic flow improvement projects (FHWA 1994). One traffic flow improvement that is becoming increasingly popular due to its low cost and high effectiveness is freeway ramp control in the form of onramp metering (Hellinga, 1995). Currently, 27 cities in the U.S. have installed ramp metering systems (or are planning systems). The largest system is composed of 800 ramp meters (Piotrowicz and Robinson, 1995) and is located in Los Angeles County (one of the most severely polluted areas in the country).

2.4 Ramp Metering

Freeway onramps are the transition link between the arterial street system and the freeway or access controlled systems. As such, ramps are unique features of the transportation system that do not always conform to traditional facility operation assumptions. For this reason they deserve special attention and study as a roadway facility. Because freeway onramps operate differently than most other facilities, ramps are characterized by different vehicle operating profiles and resulting emissions. Such differences can be compounded by the introduction of ramp controls such as ramp meters.

Arterial and onramp design features and the presence of arterial traffic signals often result in vehicles departing the arterial system and approaching approach freeway onramps in platoons (or groups). Arterial efficiency benefits from the grouping of vehicles; signal-timing progression can allow these groups of vehicles to move through progressive intersections without stopping. However, vehicles entering the freeway system as a unit can compromise the freeway flow and operation. Ramp metering devices are designed to break up vehicle platoons entering the freeway so that only one vehicle is merging onto the freeway at a time. A ramp meter is typically a traffic signal placed along a freeway onramp to pace the entry of vehicles onto the freeway. The meters are usually only operated during congested periods. A red light on the meter requires vehicles to stop before entering the freeway traffic. When the meter flashes a green light, the vehicle at the front of the queue is allowed to enter the freeway. The result is a smooth and safe vehicle transition from the arterial system to the freeway system (Piotroicz and Robinson, 1995).

Ramp metering can slow the flow of traffic onto a freeway to: 1) ensure that demand does not exceed freeway capacity, and 2) break up vehicle platoons that impair optimal freeway flows. The balanced entry of vehicles reduces the potential for freeway traffic flow breakdown and thereby significantly reduces overall system delay. Thus, mainline travel time is significantly reduced by inducing small delays on the onramps (May, 1990). Freeway flow control is optimized through a system strategy, controlling entry at numerous ramps to stabilize flow near areas that engineers consider 'critical network locations.' These network locations may include segments where freeway capacities drop, weaving areas are short and onramp volumes are heavy, or where any physical design configuration may lead to congested flow conditions. Ramp metering is most effective when implemented as a system of metered ramps in network or corridor (McShane and Roess, 1990). In addition, the benefits of ramp metering are appreciated under heavy mainline freeway demand, typically experienced during peak travel periods. Ramp metering under light traffic conditions results in little benefit to mainline travel while incurring unnecessary onramp delay.

Case studies preformed in Portland and Minneapolis have shown that peak period travel times decreased by 60 and 35 percent respectively, after the installation of ramp metering systems. In addition, ramp metering systems have also been found to reduce traffic accidents commonly associated with merging activity, such as rear-end and side swipe accidents. The result is an important safety benefit as well as an added flow improvement. The same cities experienced a 43 and 32 percent reduction in traffic accidents at the locations where ramp metering systems were installed (Piotrowicz and Robinson, 1995).

To help encourage the implementation of ramp metering and other TCMs, the USDOT has included specific funding provisions for TCMs in the last two federal transportation bills. ISTEA and TEA-21 both contained CMAQ programs. The CMAQ program specifically sets aside federal transportation funds for air quality friendly transportation improvements, such as ramp metering systems. The current legislation, TEA-21 has earmarked 8.1 billion dollars for the CMAQ program over the next six years (FHWA, 1999).

Because ramp metering increases mainline travel speeds and overall system performance, they are viable TCM projects. However, a blanket assumption that flow improvement and delay reduction yields emissions reductions is inaccurate. Such an assertion ignores the potential impact that ramp meters have on the emissions that result from changes in the operating mode of vehicles on the ramps, arterials, and mainline freeway sections. Requiring vehicles to come to a complete stop on an onramp before accelerating to freeway speed results in a measurable change in vehicle speed and acceleration rates. This change in speed and acceleration (operating mode) activity is also likely lead to changes in vehicle emissions rates. By design, ramp metering also affects the speed/acceleration (modal) activity on the mainline. Although these changes will likely be less significant than changes on the onramps, they impact a much larger number of vehicles. Emissions estimates for ramp metering systems are currently based upon predicted changes in average speeds on the mainline. Emissions impact analyses that employ average speed emission rate models, such as MOBILE5b, are insensitive to speed and acceleration interactions that lead to higher emissions. Hence, the true emissions impacts remain unclear. This is confirmed by the ramp metering emissions impact estimates calculated by agencies across the U.S., which are planning ramp metering systems as TCMs. These calculations are discussed in more detail in the following section. One basic goal of this research is to assess the emissions impacts of an entire ramp metering system through the use of a 'modal modeling' approach (which uses power demand functions based upon speed/acceleration profiles to estimate emissions). This warrants a discussion of the current and emerging vehicle emissions rate modeling regimes.

2.5 Vehicle Emissions Modeling

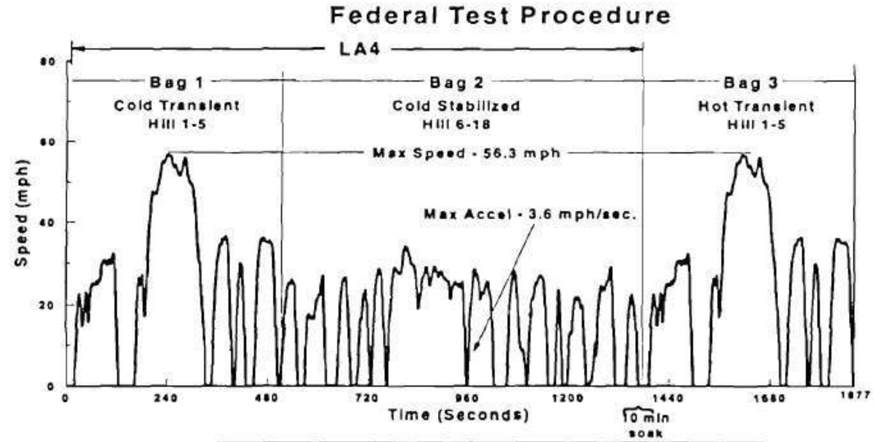
A great deal of regulatory, policy, and research attention is focused on improving motor vehicle emissions estimates. For example, the USEPA Federal Test Procedure (FTP) improvement project is redesigning the certification process to better represent onroad driving and emissions (USEPA, 1993). The average speed motor vehicle emissions modeling regimes suffer significantly from aggregation techniques employed in model development, such that the confidence bounds of model outputs make predictions less than useful from a policy perspective (Chatterjee, et al., 1997). Recent studies indicate that motor vehicle emissions are even higher than reported by the USEPA and the California Air Resources Board (CARB). Much of the research over the past several years has focused on identifying limitations in existing emissions modeling methodologies (NRC, 1991). One reason for these limitations is that the current mobile source emission rate models do not account for high power and load conditions, which produce significant emissions (Barth et al., 1996). Studies have shown that one hard acceleration event may cause as much pollution as the remaining trip and that a small percentage of a vehicle's activity may account for a large fraction of that vehicle's emissions (LeBlanc, et al., 1994). Other operating mode events, such as deceleration, also appear to produce significant emissions, and geometric conditions, which can be modeled as an acceleration against gravity, can increase emissions more than tenfold. New, statistically-based modal emissions models are being developed to provide emissions estimates as a function of disaggregate vehicle activity, or modes of operation such as acceleration, deceleration, idle, and cruise (Bachman et al., 1995).

2.5.1 USEPA MOBILE Model

The current MOBILE model, MOBILE5b, is the latest approved version of the U.S. Environmental Protection Agency's mobile source emissions rate model. MOBILE5b is a computer program that estimates the emissions rates of CO, HCs, and NOx for eight different types of gasoline and diesel motor vehicles classes. The model algorithms are used to develop emissions rates for each of the three pollutants on a grams per mile basis. Emissions estimates can then be produced by applying the emissions rate for a given average speed to the number of miles that compose a trip. The MOBILE model is used in this fashion to develop aggregate emissions estimates for a given nonattainment area for use in the mobile source emissions inventory portion of the area SIP.

The emissions rates are based on actual tailpipe emissions collected from vehicles tested on the Federal Test Procedure (FTP), which is a laboratory dynamometer test designed to replicate a typical urban commute trip. One of the primary drawbacks to the MOBILE model is that the FTP drive cycle is not necessarily representative of onroad vehicle activity. The average speed of the FTP is 19.6 mph, the maximum acceleration rate is 3.4 mph/sec^2, and the maximum speed is 56.3 mph (see Figure 2-3). The argument is that many typical urban trips include activity outside of the above ranges, or are "off cycle." To account for average trip speeds that are different from the FTP, correction factors have been incorporated into the MOBILE model, using data from vehicles tested on the FTP and other testing cycles that represent different speed and acceleration conditions. Although the correction factors allow modelers to estimate emissions for any given trip, these correction factors have been shown to underestimate emissions predictions under certain conditions. The MOBILE5b speed correction factors suggest that emissions rate vary between 0.5 and 3.0 times the FTP, while emissions test have shown that the variation can be up to 9.5 times the FTP cycle for some pollutants (Sierra Research, 1997).

Figure 2-3
FTP Drive Cycle



Test Cycle Portion	Avg Speed	Distance	Time
FTP (Entire Cycle)	21.2 mph	11.04 miles	1877 sec.
LA4 (Bags 1&2)	19.5 mph	7.45 miles	1372 sec.
"505" (Bag1 or Bag 3)	25.6 mph	3.59 miles	505 sec.

These findings indicate that the MOBILE model is inadequate for the analysis of emission impacts when applied to certain types of roadways and roadway improvements. One such type of roadway would be freeway onramps, which exhibit vehicle activity significantly different from FTP cycle. The USEPA is currently incorporating new facility specific driving cycles and other improvements into the new generation MOBILE model, MOBILE6, in an effort to address current limitation in MOBILE. While these efforts represent a substantial improvement in the accuracy of the emissions rates for use in analysis, they are still inadequate to provide an improved basis for the analysis of TCMs or many other types of roadway improvements. Therefore, even the newest version of the MOBILE model, MOBILE6, (which had not been released at the time of this research) would not be ideal for the assessment of TCMs such as a ramp metering system. This notwithstanding, the MOBILE model (or equations developed from application of the MOBILE model) is currently used by most air quality and planning agencies outside of California for assessing the benefits of TCMs. Areas in California use the CARB EMFAC model, which is also an average speed emissions rate model similar to the MOBILE model. A new generation of dissagregate emissions models are being developed that have potential for providing a basis for a greatly improved analysis method for many different transportation improvements, including TCMs.

2.6 MEASURE Aggregate Modal Emission Rate Model

Georgia Tech has made significant progress in the development of a modal modeling framework known as MEASURE (Mobile Emissions Assessment System for Urban and Regional Evaluation)(Bachman, et al., 1996; Guensler et al., 1997). MEASURE is a modeling framework designed to link specific vehicle activity and emissions rate data, within a geographic information system (GIS). The GIS serves as a tool for storing all of the spatial and temporal attributes of the modeling regime, and integrating a wide variety of data sources, spatial attributes, and temporal distributions for use by external programs to estimate emissions. The coded GIS contains the transportation network physical characteristics (link length, number of lanes, roadway grade, etc.), terrain, roadway operational characteristics (capacity, vehicle mix, etc.), analysis zones, intersections, onramp locations, and other locations of potential enrichment activity.

The basic point of departure of the new emissions modeling algorithms incorporated into MEASURE is that mobile source emissions are a function of vehicle operating profiles such as cruise, acceleration, deceleration, idle, and other power demand conditions that lead to enrichment (high fuel:air ratios) rather than a function of average speed. In developing the aggregate modal model, the team employed a variety of advanced statistical techniques to the existing laboratory testing data. The model is based upon the same data that were used to develop the MOBILE5b model (average grams/second emissions test results for each pollutant for each vehicle on each laboratory testing cycle). However, instead of predicting emissions as a function of average speed, the statistical methods were designed to predict test result emissions as a function of various power-demand operating characteristics present within these driving cycles. Ongoing field and emission laboratory measurements are being used to validate and further refine research findings.

The Aggregate Modal Model emission rates within MEASURE were developed using a regression tree analysis of available dynamometer tests. The comprehensive database contains 30,834 test results from 19,092 vehicles on the FTP and 17,417 test results from 8171 vehicles on alternative hot-stabilized testing cycles (Wolf, et al., 1998). Advanced statistical methods were applied to the data to develop an improved emission rate model (Washington, et al., 1998; Fomunung, et al., 1999). Inherent in such a modeling approach is the replacement of nominal driving cycle assumptions with actual vehicle operating mode (speed/acceleration) distributions. To evaluate transportation projects and strategies to reduce congestion and delay, it is therefore necessary to evaluate the effects of proposals on activity operating mode patterns.

The next chapter addresses both MOBILE5b and the MEASURE Aggregate Modal Model emission rate algorithms used to estimate the air quality impacts of the ramp metering system in Atlanta. This research has identified how ramp metering impacts the overall changes in vehicle operating patterns along the mainline freeway and onramp, and estimated the resulting emissions impacts using applicable MEASURE emission rates and MOBILE5b emissions rates. Vehicle technology and activity measures were combined with technology and modal specific emission rates to produce the estimates. Vehicle technology distributions were developed from the registered fleet of automobiles in the study area (i.e. those using the I-75 corridor).

2.7 Ramp Metering and Vehicle Emissions

When ramp metering is implemented, stop-and-go congestion on the freeway segment is reduced and delay and acceleration (from stop to freeway speeds) for vehicles at the onramps is increased. Ramp delays before and after metering systems are installed, can change significantly (ITE, 1992). The vehicle operating modes along the mainline and the onramps both have the potential to change dramatically due to introduction of ramp meters. Large acceleration changes can result for the small number of vehicles entering the freeway, and smaller changes in operating modes (i.e. cruise, idle, acceleration, and deceleration) occur for large numbers of vehicles operating on the freeway. The general public sentiment is that emissions under most ramp metering scenarios are expected to be less than non-metered scenarios because the onset of traffic flow breakdown can be significantly delayed through ramp metering. However, it is unclear to what extent the increase in hard acceleration activity on the onramps and the increased vehicle speeds on the mainline freeways increases emissions.

One estimate of ramp metering systems using MOBILE emissions rates, showed that ramp metering increases emissions levels. An evaluation of a proposed ramp metering system in Birmingham concluded that the system would result in an increase in both HC and NOx emissions. The study speculated that the emissions increase was due to the fact that the system was proposed in a relatively uncongested corridor and that the operational benefits were small as a result. The study estimated that the ramp metering operations would only result in a one mph increase in mainline travel speeds. As a result, the small emissions benefit estimated by MOBILE due to the improved travel speed would be offset by the increased ramp emissions brought about by lower average speeds on the ramps (PBSJ, 1995). A similar TCM analysis study performed for the Pennsylvania Department of Transportation estimated that ramp metering would result in a four percent increase in average peak period freeway speeds. However, this study concluded that this resulting flow improvement would result in a net decrease in vehicle emissions rates (COMSIS, 1994).

Apart from the assessment of ramp metering systems as TCM projects, there are only two significant ramp metering air quality studies found in the literature. These include a 1997 Sierra Research study (conducted as part of NCHRP 8-33) and a 1993 California Department of Transportation study by Edward Sullivan.

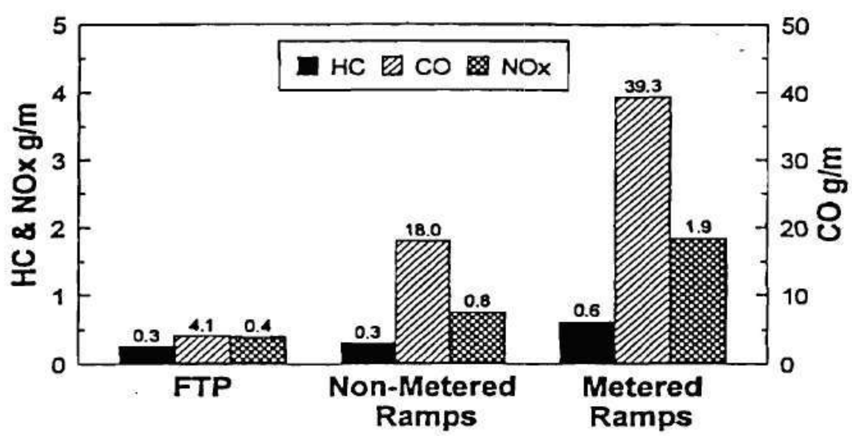
The Sierra Research report documents the process and findings that were undertaken to investigate vehicle emissions associated with driving on freeway onramps as part of a project to improve the air quality analysis methodology for TCM projects. This project included the collection of onramp speed and acceleration activity used for the development of two ramp drive cycles. One drive cycle was developed for vehicle activity on freeway onramps under ramp metering conditions and the other was for non-metered conditions. The activity data used for the development of the drive cycles were from a limited amount of data from the Sacramento California area, collected through the use of an instrumented chase car. Once the two drive cycles were established, emissions tests for four mid to late model vehicles were preformed on a chassis dynamometer. Table 2-2 shows the operating parameters for the two cycles (Sierra Research, 1997).

Table 2-2
Comparison of Sierra Research Metered and Non-Metered Ramp Driving Cycles

Operating Condition	Average Speed (mph)	Maximum Speed (mph)	Maximum Acceleration Rate (mph/sec)	Length (miles)
Metered	15.1	55.3	8.1	1.42
Non-Metered	40.8	61.4	4.6	2.93

Part of this report included a comparison of the emissions from the two drive cycles with that of the emissions from the average FTP cycle. Figure 2-4 shows the average HC, NOx, and CO emissions for the metered, non-metered drive cycles, and the FTP cycle for four mid to late model passenger cars. As can be seen, the emissions on a grams per mile basis are highest for the metered conditions and lowest for the FTP cycle.

Figure 2-4
Average Emission Rates on Metered, Non-Metered Ramps and FTP Driving Cycles
Sierra Research 1997



Previous studies indicate that average speed emissions rate models are inadequate for use in TCM analysis. The Sierra Research (1997) study indicated that ramp metering may result in a significant increase in vehicle emissions from the ramps. However, the Sierra Research study suffers from several drawbacks. First, this study is based on limited modal activity data and therefore the drive cycles may not be representative of actual average driving behavior. Second, there was no effort made during this study to control for effect of ramp geometry or length. Third, the emissions estimates were based on a limited number of vehicles (four). Fourth, this study only considered changes in vehicle activity on freeway onramps and did not account for changes in mainline activity. Although the Sierra Research (1997) study provides some important information about the emissions impacts of ramp metering, the findings were limited and inconclusive (given the limited number of vehicles and variability in vehicle response to the changes in operating modes).

The Sullivan report *Vehicle Speeds and Accelerations Along Onramps: Inputs to Determining the Emissions Effects of Ramp Metering* provides more data than the Sierra Research study, but suffers from its own limitations. In the Sullivan study, speed and acceleration data were obtained and analyzed for nineteen freeway onramp locations in urbanized areas of four different Caltrans districts (located throughout California). The Sullivan study sample was split between ramps with and without ramp meters and included ramp speed and acceleration data with and without mainline congestion. The primary product of the Sullivan study was to develop a comprehensive data set describing the speed and acceleration of light-duty vehicles along onramps under various conditions with an emphasis on the presence or lack of presence of ramp meters. The intent was to develop a data set that could feed modal specific emissions models, but since this modeling was not part of the Sullivan study, actual emissions estimates were not determined. In addition, the Sullivan study only evaluated ramp activity and did not include observations of vehicles operating on the mainline. Although the Sullivan study provides important modal activity information for vehicles operating on freeway onramps, it does not provide any conclusive findings regarding the emissions impacts resulting from the changes in modal activity.

This GDOT research project improves on these past studies in several important areas. First, a freeway system data set, including ramp and mainline activity, was collected. In addition to including vehicle modal activity profiles for metered and non-metered conditions, this research included data for varying ramp designs and mainline flow conditions. Third, the modal activity data collected as part of this research were used to drive a modal emissions rate model to produce enhanced emissions estimates. The next chapter discusses these improvements and the overall research approach in detail.

CHAPTER 3
FIELD RESEARCH APPROACH

This chapter presents the basic research approach for performing an evaluation of the air quality impacts of a ramp metering system using field data collection methods. First the problem is defined, followed by presentation of the research hypothesis and research objectives. This is followed by a detailed discussion of the research scope of work. Data collection and analysis techniques considered for this research and the emissions modeling procedures are then outlined. This discussion provides the basis for the data collection plan and analysis procedures, which is addressed in the subsequent two chapters.

3.1 Problem Statement

As discussed in the previous chapter, despite advancements in pollutant emissions control brought about by the Clean Air Act and its amendments, urban air quality is still a serious problem throughout the U.S. Concurrent with this air quality problem, urban areas in the U.S. are experiencing a rapid increase in traffic congestion and travel delay. Indeed, growth in vehicle ownership and travel activity (more and longer trips), is resulting in an increase in the number of vehicle miles of travel (VMT), which is directly contributing to the increase in mobile source emissions and traffic congestion.

In light of diminishing capital funds and physical constraints on the construction of new transportation facilities, traffic congestion is being addressed by transportation professionals through optimization of the existing infrastructure. This optimization is accomplished through a variety of transportation management strategies, and federal agencies are encouraging the implementation of transportation control measures (TCMs) designed to simultaneously reduce congestion and motor vehicle emissions. One frequently implemented transportation program is freeway ramp metering, which is particularly popular due to its cost effectiveness for reducing congestion levels.

Traffic flow and travel time benefits of ramp metering are well documented in the literature (Piotrowicz and Robinson, 1995; Meyer, 1997), but the true emissions and air quality benefits are not. Therefore, the question of the air quality impacts of ramp metering remains unanswered. This is an important question in light of the current urban air quality and traffic congestion problems, given the fact that many cities are using ramp metering as a TCM in an effort to reduce vehicle emissions.

One reason that the emissions impact of ramp metering has been difficult to estimate is that the modeling regimes used to estimate vehicle emissions are not suited for the analysis of small scale traffic improvements such as ramp metering. The MOBILE series of average speed emissions rate models are aggregate models that are not sensitive to high emissions activity encountered on freeway onramps equipped with ramp meters. Emerging disaggregate modeling regimes, such as the MEASURE Aggregate Modal Model provide a basis for providing more accurate emissions estimate for ramp metering systems.

This analysis provides critical information to transportation planners and engineers regarding the comprehensive impact of a ramp metering system due to changes in modal activity brought on by ramp metering systems. This information can then be used to determine if a ramp metering system is an appropriate strategy depending on the particular air quality and congestion problem of a given area.

3.2 Research Hypotheses

Enrichment conditions for vehicles operating on onramps are likely to increase under metered conditions as vehicles accelerate rapidly to freeway speeds. The magnitude of the resulting emissions increase is uncertain, but most analysts anticipate that the negative ramp emissions impacts will be more than offset by positive emissions benefits from improved flow conditions on the mainline freeway segments. This would result from smoother operation on the mainline resulting in less enrichment and lower power demand and more efficient combustion. Because the number of vehicles operating on the mainline is much greater than that of the ramps, the net result is generally believed to be a decrease in vehicle emissions under congested traffic conditions. Therefore the research hypothesis is:

> **Ramp metering systems operating under peak period traffic demand will yield an increase in ramp HC, CO and NOx emissions, a decrease in mainline HC, CO and NOx emissions, and a net decrease in emissions for the combined system**

To assess the emissions impacts of ramp metering systems, this research had four main objectives:

> **Objective 1: Develop a method to sample representative modal activity on freeway onramps and mainline sections of the Atlanta ramp metering system**

To assess the emissions impacts of a ramp metering system using a dissagregate modeling approach, where emissions are predicted as a function of the way that vehicles are driven, it was necessary to gather speed/acceleration profile (modal activity) data. In addition to developing a representative sampling procedure, the data collection plan also needed to address issues of gathering data across all locations of the system simultaneously. The focus of this objective was on sampling modal activity data for passenger vehicles, although other vehicles such as trucks were not excluded from the sample. The sampling plan also included collecting modal activity data for both metered and non-metered conditions to provide data for a direct comparison of both conditions.

> **Objective 2: Utilizing the modal activity data collected from the system as an input to the Aggregate Modal Model algorithms in MEASURE, estimate changes in vehicle emission rates and net vehicle emissions resulting from operations of ramp meters.**

The prime objective of this research is to determine the emissions and air quality impacts of a ramp metering system. Using the Atlanta system as a case study, researchers estimated vehicle emissions on ramps and mainline freeway segments, with and without the ramp meters in operation. Analyses included assessment of field-monitored vehicle activity operating conditions as well as simulated vehicle activity operating conditions.

Objective 3: Compare the emissions estimates for the Atlanta ramp metering system from the MEASURE Aggregate Modal Model to the emissions estimates produced by the USEPA MOBILE5b model.

The MOBILE series of emissions rate models produce inaccurate emissions estimates for some applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). In most cases, MOBILE emissions estimates are below observed onroad emissions rates due to the lack of sensitivity to off-cycle enrichment activity, such as hard accelerations. In addition, MOBILE is considered to be inappropriate for small-scale analysis, for example TCM evaluation. One objective of this research was to validate this limitation through a comparison of the current MOBILE model, MOBILE5b, estimates with the MEASURE Aggregate Modal Model estimates.

Objective 4: Assess prevailing mainline flow conditions and ramp configurations and designs (e.g. grade and acceleration distance) that influence ramp and mainline modal activity.

A final objective of this research was to determine the flow and design conditions that influence vehicle modal activity within the ramp metering system. The operational benefits of ramp metering are not realized under light traffic flow. That is, the delay realized by vehicles on the ramps is greater than the benefit gained to mainline traffic if ramp metering is implemented under low traffic volumes. Therefore ramp metering is typically only used under heavy traffic flow or during peak travel periods. The question this research answered was, under what traffic flow conditions (i.e. level of service) is the vehicle modal activity increased. In addition, the ramp geometry (e.g. grade and acceleration distance) and configuration (e.g. with or with out an auxiliary lane, loop ramp, etc.) was examined to assess the potential influence on modal activity.

3.3 Scope of Work

Several tasks were undertaken to guide and complete the field aspects of the overall research effort. The overall scope of the fieldwork was divided into eleven primary steps including the previously discussed hypothesis statement and research objectives. The eleven research approach steps were:

1. Statement of Hypothesis and Research Objectives
2. Define Target Group/Population
3. Identify Relevant Data to be Collected
4. Determine the Degree of Data Precision
5. Develop Survey/Data Collection Methods
6. Determine Sampling Units
7. Determine Sampling Procedure and Sample Size
8. Pretest Survey Method and Field Procedures
9. Develop Survey Management Structure
10. Develop Analysis, Reduction and Summary Procedures
11. Develop Data Storage System

The research hypotheses were outlined earlier. A detailed description of each of the remaining ten steps is addressed in detail in subsequent subsections.

Step two, *the definition of the target group*, may seem obvious for this research, but needs to be outlined. The target group for this study included vehicles operating on the freeway onramps and mainline section in the study area. All vehicles were included in the study, although the focus of the analysis is on passenger vehicles. Data were collected on all vehicles sampled in the study area in order to provide fleet mix information and a complete data set, but the emissions analysis was only performed on passenger vehicles (including SUVs). There are two reasons for this. One, emissions algorithms for heavy-duty vehicles have not been implemented in the MEASURE Aggregate Modal Model. Secondly, the majority peak period vehicle activity is associated with passenger vehicles.

The third step, *identify relevant data to be collected*, focuses on the information needed to perform the proposed research analysis. The data needed for this project is divided into two primary groups, one being vehicle activity data and the other being system information. The necessary vehicle activity data consists of instantaneous speed/acceleration profiles for a large sample of vehicles operating on the ramps and freeway mainline sections. Detailed data collection of operating conditions on the arterials was precluded by resource limitations and was not included in the original scope of analysis. The vehicle speed/acceleration profiles provides the core data for this research and is the critical information that was used to tie changes in vehicle operating modes with changes in emission rates. The system data include physical ramp and roadway characteristics, such as grade, curvature, acceleration distance, ramp design, and ramp metering rate. In addition, system traffic flow data were also included. This consisted of ramp and mainline 15-minute flow rates, lane distributions, average vehicle speeds, truck percentage and vehicle mix, and vehicle characteristics (e.g. engine type, fuel type, emissions control, transmission type, and accumulated mileage). For this research, only evening peak period conditions were of concern, since the ramp meters in the study area only operated during these peak hours of travel to assist with the outbound commute.

Step four, *determine the degree of analysis precision*, was performed in conjunction with the previous step. Once the relevant data are determined, the analysis precision needs to be established in order to refine the data collection methods. This study focused on vehicle activity at the microscopic level (i.e. second-by-second individual vehicle activity). Detailed speed/acceleration profiles were collected for a sample of vehicles operating in the study area. This empirical information was then used to draw conclusions regarding the operation of all vehicles in the fleet and as an input to the MEASURE Aggregate Modal Model and MOBILE5b. Therefore the activity data analysis was designed to be highly precise, although some findings were presented in the aggregate and as the average or variance of the discrete data points.

The fifth step, *develop survey/data collection methods*, is the process of gathering the data that has been identified as necessary for the research. For this project, survey and data collection procedures entailed the collection of several components of vehicle activity. First and foremost, this included the collecting of vehicle speed/acceleration profiles on the onramps and mainline sections of the study area. Secondary to this was the collecting of traffic volumes and vehicle license plate information. The speed/acceleration data and the license pate data were collected from only a sample of vehicles in the study area during the evening peak study period. Data collection activities were performed during a four-hour evening peak period (3:00pm to 7:00pm) on eighteen weekdays. Four of the data collection days were conducted while the ramp meters were turned off. Chapter 4 is dedicated to a description of the data collection process, site selection, and field procedures.

Determine sampling units, was step six. Data are collected from individual vehicles, but individual vehicle data were binned into groups for analysis. Data bins were developed by location and time. In general, data from each ramp location and each mainline data collection site were grouped into fifteen-minute time bins. That is, for reasons that are discussed in later sections, the vehicle activity data with similar characteristics were analyzed in groups, and not as individual traces.

The related seventh step, *determine sampling procedure and sample size*, was developed in order to acquire a random sample that would provide the appropriate amount of data for the analysis. A sampling procedure was developed for each data collection site to yield a random and unbiased sample of vehicles. These procedures are discussed in the following Chapter 4. The necessary sample size was not known prior to the data collection phase and ultimately was determined by the resources available. That is, all available data were collected given the time and fiscal constraints stated above.

Step eight, *pretest survey method and field procedures*, was performed once the data collection process was refined. To gather the necessary data for this analysis, up to fifteen data collectors were required to be in the field at any given time during the process. Therefore, it was important to pre-test the methods and procedures before final collection deployment. The pretest for this research included four days of "dry" runs and data sampling tests.

Step nine, *develop survey management structure* was also performed before data collection was initiated. This entailed determining the appropriate data collection staff, field deployment and equipment setup procedures, safety procedures, and standard operating procedures for data collectors. This also included procedures for downloading, storing and archiving the field data.

Step 10, *develop analysis, reduction and summary procedures* was being performed before step 9 was complete. This ensured that the data collection process resulted in information that would fit the proposed analysis procedure. The primary thrust of this data collection was to gather vehicle speed profile information that could be used to develop joint acceleration-speed probability density functions (JASPROD), for use as inputs to modal emissions models and other vehicle modal activity procedures. This also included the transformation of the field data and measurements in to information that was meaningful and could be easily analyzed.

The eleventh and final step, *develop data storage system*, consisted of constructing a database system for all of the data elements. Once the data were collected it was important to have a data storage routine so that it could be easily cleaned, processed, and analyzed. Again, the details of the database system and the other data collection and processing procedures are discussed in the following chapter. The following sections of this chapter discuss the specifics of the analytical procedures.

3.4 Analysis Procedures for Field Efforts

One of the most critical components of the research approach is the analysis procedure. These procedures define how the four research objectives were accomplished. The analysis procedure for the field research is divided into three primary components. These consist of: 1) the vehicle NOx emissions analysis of the Atlanta ramp metering system using the MEASURE Aggregate Modal Model emissions rate algorithms to estimate the vehicle emissions, 2) a comparison of the MEASURE Aggregate Modal Model and MOBILE5b estimates, and 3) an assessment of the traffic flow and ramp geometric design conditions influence on vehicle model activity levels and related estimated emissions rates.

3.4.1 Emissions Analysis

The Georgia Institute of Technology MEASURE Aggregate Modal Model, described in Chapter 2, is the basis for the emissions analysis. The Aggregate Modal Model is designed to be implemented on a regional level and incorporates numerous elements of mobile source emissions, including start emissions, evaporative and running exhaust emissions. This research is only concerned with changes in hot stabilized running exhaust emissions and therefore only incorporates certain sub-elements of the model. In short, the emissions rate algorithms, (which comprise just one component of the model), are the only element used for this analysis. Although only a single component of the overall MEASURE GIS-based modeling framework, these emissions rate algorithms are one of the distinct elements of the MEASURE framework.

The Aggregate Modal Model hot stabilized emissions rate algorithms were established from a data set of more than 13,000 dynamometer tests. The algorithms predict emissions rates of motor vehicles grouped by various technology criteria as a function of aggregate measures of vehicle speed and acceleration profile. The vehicle activity related variables modeled in the MEASURE framework include average speed, acceleration rates, deceleration rates, and surrogates for power demand imposed on the engine. The following section provides a description of the MEASURE Aggregate Modal Model algorithms.

3.4.1.1 Structure of the MEASURE Aggregate Modal Model Algorithms

Separate Aggregate Modal Model algorithms (Fomunung, 1999) are used in MEASURE for each of the pollutants of concern, CO, HC, and NOx. Each algorithm is statistically derived using a combination of parametric and non-parametric methods. Each of the three algorithms are presented in a functional form.

The CO model is based upon the regression equation:

$$\begin{aligned}\text{Log}R_{CO} &= 0.0809 + 0.002*\text{AVGSPD} + 0.0461*\text{ACC.3} + 0.0165*\text{IPS.60} - \\ &0.0283*\text{ips45sar2} + 0.3778*\text{ips90tran1} - 0.0055*\text{tran3idle} + 0.1345*\text{tran5mi1} \\ &+ 0.3966*\text{finj3sar3} - 0.0887*\text{cat3tran1} - 0.2636*\text{sar3tran4} - 0.481*\text{flagco}\end{aligned} \tag{3-1}$$

(Fomunung, 1999)

Where:

R_{CO} is the emission rate ratio for each vehicle technology group (the gram/second emission rate under the observed conditions divided by the gram/second emission rate under standard FTP laboratory test conditions);

AVGSPD is the average speed of the driving cycle in mph;

ACC.3 is the proportion of the driving cycle on acceleration greater than 4.8 kph/s (3mph/sec);

IPS.60 is the proportion of the driving cycle on inertial power surrogate (IPS) (speed x acceleration) greater than X mph2/sec (Washington et al., 1994). Thus, IPS.60 implies IPS greater than 60 mph2/sec;

ips45sar2 is an interaction between IPS.45 (IPS >= 45 mph2/sec) and a vehicle with no air injection;

ips90tran1 is an interaction variable for a vehicle with automatic transmission on IPS.90 IPS >= 90 mph2/sec;

cat3idle is an interaction variable for a 3-speed manual transmission at idle;

tran5mi1 is an interaction variable for a 5-speed manual transmission vehicle with mileage <= 25k miles;

finj3sar3 is an interaction variable for a vehicle that has throttle body fuel injection and pump air injection;

cat3tran1 is an interaction variable for a vehicle with automatic transmission and TWC;

sar3tran4 is an interaction variable for a vehicle with 4-speed manual transmission and pump air injection; and

flagco is a flag used to tag a high emitting vehicle under CO emissions.

The HC model is based upon the regression equation:

$$\mathrm{Log}R_{HC} = 0.0451 - 0.6707*\mathrm{my79} - 0.1356*\mathrm{my82} + 0.019*\mathrm{AVGSPD} + 0.2021*\mathrm{finj2tran4} + 0.1795*\mathrm{cat2sar1} + 0.1651*\mathrm{cat3sar1} + 0.0318*\mathrm{cat3sar2} - 0.1189*\mathrm{sar3tran1} + 0.5646*\mathrm{sar1tran5} + 0.0004*\mathrm{cid} - 0.2581*\mathrm{sar3kml} - 0.0169*\mathrm{finj2km3} - 0.5144*\mathrm{flaghc} - 0.0129*\mathrm{acc1finj2} - 0.1626*\mathrm{acc3cat2} - 0.3891*\mathrm{ips90sar3} + 0.0307*\mathrm{dps8finj2} \quad (3\text{-}2)$$

Where:

R_{HC} is the emission rate ratio for each vehicle technology group (the gram/second emission rate under the observed conditions divided by the gram/second emission rate under standard FTP laboratory test conditions);

my79 = model year < 79;

my83 = 79 < model year < 83;

AVGSPD = average vehicle speed (mph);

finj2tran4 = interaction variable for a 4-speed manual transmission vehicle with a carburetor;

cat2sar1 = pre 1981 model year vehicle with "oxidation only" catalyst and unknown air injection type;

cat3sar1 = pre 1981 model year vehicle with a TWC and unknown air injection type;

cat3sar2 = vehicle with TWC and no air injection;

sar3tran1 = automatic transmission vehicle with pump air injection;

sar1tran5 = pre-1981 model year, 5-speed manual transmission vehicle of unknown air injection type;
cid = cubic inches displacement;
sar3km1 = vehicle with pump air injection and mileage <=25k miles;
finj2km3 = vehicle with pump air injection and 50k < mileage <= 100k miles;
flaghc = high emitting vehicle flag under HC emissions;
acc1finj2 = carburetor-equipped vehicle operating with acceleration greater than 1 mph/s;
acc3cat2 = oxidation only catalyst vehicle with acceleration greater than equal to 3.0 mph/s;
ips90sar3 = vehicle with air pump and inertial power surrogate greater than or equal to 90 mph2/s; and
dps8finj2 = proportion of drag power surrogate (DPS) speed x speed x acceleration) greater than 8 mph3/s.

The NOx model is based upon the regression equation:

$$\mathrm{Log}R_{NOx} = -0.5864 + 0.0225AVGSPD + 0.3424*IPS.120 + 0.6329*ACC.6 + 0.0247*DEC.2 + 0.0083*finj2km1 + 0.0028finj2km2 - 0.0021*cat2km3 + 0.0026*cat3km2 + 0.0003*cat3km3 - 0.0085*finj1km3flagnox - 0.0068*finj3km3flagnox \quad (3\text{-}3)$$

Where:

R_{NOx} is the emission rate ratio for each vehicle technology group (the gram/second emission rate under the observed conditions divided by the gram/second emission rate under standard FTP laboratory test conditions);
IPS.120 = proportion of activity where IPS >= 120 mph2/sec;
ACC.6 = proportion of activity where acceleration >= 6.0 mph/s;
DEC.2 = proportion of deceleration <= -2.0 mph/s;
finj2km1 = carburetor equipped vehicle with mileage < 25k miles;
finj2km2 = carburetor equipped vehicle with 25K, mileage <= 50k miles;
cat2km3 = "oxidation only" catalyst vehicle with 50k < mileage <= 100k miles;
cat3km2 = TWC vehicle with 25K mileage <= 50k miles;
cat3km3 = TWC vehicle with 50K < mileage <= 100k miles;
finj1km3flagnox = second order interaction variable for a high emitting vehicle with port fuel injection and 50k < mileage <= 100k miles; and
finj3km3flagnox = second order interaction variable for a high emitting vehicle with throttle body fuel injection and 50K < mileage <= 100k miles.

To use these modal algorithms, accurate input data must be provided. Two main types of data drive these emissions models: 1) modal activity data in the form of speed/acceleration profiles, and 2) vehicle characteristic data. It is possible to use default activity and vehicle data that would be representative of the fleet in general in conjunction with these models. However, this research proposes to employ detailed activity data collected in the field as opposed to a generalized study. Rather than using average speed/acceleration profiles and regional fleet data, the research team collected specific vehicle characteristics and representative speed/acceleration data from vehicles operating on freeway and freeway onramps. Hence, model inputs are based upon the fleet and modal activity data present on the system.

3.4.1.2 Vehicle Speed/Acceleration Profiles

To generate speed/acceleration profiles for ramp and mainline flows, vehicle trajectories are required. Previous Georgia Tech research assessed a variety of procedures for collecting speed/acceleration profiles (Grant, 1997a; Grant, et al., 1998). In 1996 and 1997, researchers assessed the capability of video data processing as a means of collecting accurate vehicle trace data. The researchers determined video resolution limitations, coupled with vibration and camera angle problems, and constrained acceleration data below the desired accuracy level for modal emissions modeling. Hence, supplemental means were developed to collect vehicle trace data. Two alternative approaches are typically employed: 1) laser rangefinders (LRFs) record traces for a large subset of vehicles over a relatively short distance (1000 to 2000 linear feet), and 2) floating cars equipped with onboard instruments are introduced into the fleet to record traces of a few vehicles over the entire monitored facility.

LRFs are field-proven and are effective in collecting speed/acceleration profiles. Thus, LRFs were relied upon extensively to perform data collection for this analysis. However, floating cars equipped with distance measuring equipment were also used to collect speed acceleration profiles for some areas. Specifically, floating cars were utilized to collect data on mainline sections and curved sections of onramps where use of laser rangefinders was not effective or practical.

LRFs were used to capture the speed-acceleration profile of vehicles operating on onramps and mainline segments. Laser Atlanta's Advantage LRFs were employed in the field study. The Advantage LRFs integrate faster components and new software that significantly improved the performance of these hand-held laser devices compared to those used in previous studies. Accuracy is 0.5 foot with a precision of 0.1 foot. The LRF operates by recording a vehicle location at a rate of 238 times per second, with speeds and accelerations of vehicles computed based upon these distance measurements. Variables used by the Advantage are programmed through a keypad on the rear face of the unit, thus not requiring a laptop computer and cables to make modifications. In addition, portability is excellent with the battery unit in the handle of the gun and lightweight casing materials.

Data from the Advantage laser gun can be sent to a computer hard drive via serial port interface or written directly to an internal PCMCIA card (which inserts into the rear of the laser gun unit). The serial port interface allows a transmission rate up to 115.2 kBaud. The extremely transfer high rate, when compatible with the portable computer, allows storage of ASCII data directly to a file. Another method of storage is a SRAM PCMCIA card, which stores all data, streamed to the output port in null data files created on the card. In real-time range mode, when a trigger is pulled all data are stored to the first available null data file on the PCMCIA card. A subsequent pull of the trigger stores every range reading to a separate file on the PCMCIA card.

The LRFs were operated from tripods along the onramps and overpasses to record the full trace of onramp activity, from onramp entry to merging with freeway traffic. The geometry of two of the sites required setting one LRF at the beginning of the onramp and one LRF in the shoulder of the ramp near the ramp stop bar to capture the full activity of each vehicle from entrance on the ramp to freeway merge. Modal activity of freeway traffic along the merge areas, weave areas, and basic freeway sections was captured by locating LRFs along the overpass at several different locations. Details of the data collection locations are provided in Chapter 4.

Dual locations of the LRFs were necessary to record the speed and accelerations of vehicles as they entered the ramp and approached the stop bar, then as the vehicle left the ramp meter and merged with traffic. The core of this research is to verify if the "hard" accelerations that send a small number of vehicles into enrichment at the onramp may significantly reduce the emissions benefit received by "smoothing" traffic along the mainline freeway section. Therefore, the focus of the LRF data collection effort was to record information as vehicles accelerated from the stop bar down the ramp to the merge area. For this reason, the data collection procedures and analyses separated vehicle onramp activity into two zones. The acceleration zone (described above) and the deceleration zone, which is the length from the start of the onramp to the ramp meter stop bar location.

LRF field-testing revealed range limitations for tracking vehicle activity. The distance that automobiles can be tracked is limited by line-of-sight, obstructions such as light standards, trees, and signage, as well as interference from other traffic. Automobiles can be reliably tracked for 1000 to 1500 feet. The maximum distance at which the laser will "lock on" to an automobile is approximately 1500 feet, with the most consistent data collected at shorter distances. Data returned from trucks and larger vehicles are more reliable because of the large front or rear area they provide for computing ranges. Distance reliability is potentially more of a problem in heavy traffic when vehicles appear close together. The data collection efforts for this project required the use of seven LRFs to collect the necessary speed/acceleration profiles. The seven LRFs provided for concurrent coverage of the four onramp and mainline, ramp metering system.

To supplement flow measurements along the mainline, two instrumented floating vehicles captured the flow of traffic using car following techniques. The instrumented vehicles allow for speed-acceleration measurement of vehicle flow in areas where the LRF cannot measure due to observation location constraints. Onboard instrumentation has been used extensively as a means to measure speeds and accelerations of onroad vehicles. The instrumentation has been used to quantify the modal activity of a large random sample of vehicles along the road using a car-mounted laser rangefinder to compare relative change in speed to that of the instrumented vehicle (Austin, et al, 1993). Other distance measuring instruments have been used to measure speeds and accelerations of a floating car for energy consumption analysis (Eisele, et al., 1996). This research seeks to expand the existing data collected to evaluate the impact of the ramp metering on operations of vehicles along the onramps and mainline freeway segments through a combination of remote sensing and floating car data.

The research team equipped two floating cars with distance measuring instruments (DMI). A DMI is installed on the vehicle by attaching magnets and a magnetic pulse counter to the transmission of the vehicle. The DMI records the number of transaxle pulses and translates the pulses into distance traveled. Traveled distance is measured with precision to the nearest foot at

1 Hz. The accuracy of the equipment is as good as the calibration procedure, with precision to the nearest foot. Sampling of the distance traveled is completed by a BASIC program, which saves the distance the vehicle has traveled once per second.

The speed/acceleration traces acquired from both the instrumented vehicles and the LRFs were used to develop speed/acceleration profiles. These profiles were then used to summarize vehicle modal activity, assess variations in modal activity, and feed the modal activity equations in MEASURE.

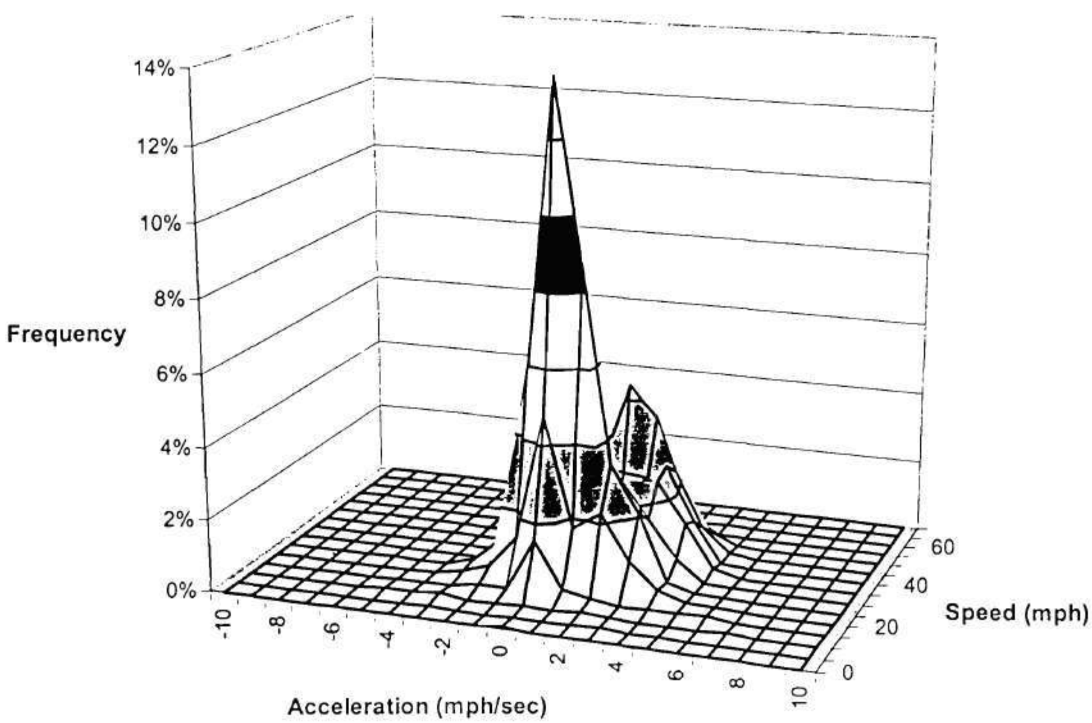
The speed/acceleration data were transformed into a JASPROD, which is a three-dimensional (tri-variable) function of speed, acceleration, and the joint probability for a given speed-acceleration bin (Watson, et al, 1982). These JASPRODs are often referred to as Watson plots. An empirical JASPROD is created by sampling the simultaneous speed and acceleration trace of a vehicle along a specified path (or cycle), such as a vehicle's trajectory from the point of queuing to some point downstream. Data were processed in one-second intervals so the resulting JASPROD are for one-second intervals. Parsing the second-by-second vehicle activity into a matrix of speed-acceleration bins creates each JASPROD. Each bin has a unique speed and acceleration range. A JASPROD is shown in both matrix form and graphic form in Table 3-1 and Figure 3-1. The probability of activity occurring in a bin is calculated by dividing the bin frequency by the sum of all bin frequencies. For each given geometric and operational condition investigated, the frequency of activity in a specific speed-acceleration bin is the number of seconds of operation in a given bin divided by the total number of seconds of activity. The sum of all frequencies for a vehicle trace equals one.

The MEASURE Aggregate Modal Model employs fractions of vehicle activity under specific modal conditions which have been shown to correlate with emission rates (i.e. the percent of activity where acceleration >= 6.0 mph/s). Vehicle activity data can be directly linked to applicable emission rate equations. However, a method that links each JASPROD with the emission rates is more desirable, since response variables may change in the future depending on results of ongoing emission rate modeling. This way, the activity data collected in this study can be used with any future emission rate model that identifies critical modal variables, as well as for other types of analysis. For example, if a 3-dimensional activity distribution is available and future research identifies acceleration greater than 5 mph/s as significant, the total fraction of activity that falls within this range can be selected from the JASPROD.

Table 3-1
Matrix Form of a Joint Acceleration-Speed Probability Density Function (JASPROD)

Speed	Acceleration (mph/sec)																				
(mph)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	1	0	0	1	0	1	2	0	1	0	0	0	0	0
10	0	0	0	0	0	2	2	4	0	1	2	1	3	1	0	0	0	2	0	0	0
15	0	0	0	0	0	1	1	1	6	6	54	11	6	2	3	3	4	0	0	0	0
20	0	0	0	0	0	0	1	6	15	45	162	60	76	35	11	3	2	1	0	0	0
25	0	0	0	0	1	0	1	8	31	188	466	297	114	71	9	2	1	0	0	0	0
30	0	0	0	0	0	0	0	0	4	12	22	60	92	57	22	2	1	1	0	0	0
35	0	0	0	0	0	0	0	0	1	1	0	1	22	85	47	7	0	0	0	0	0
40	0	0	0	0	0	0	0	0	3	3	6	8	31	91	40	2	0	0	0	0	0
45	0	0	0	0	0	0	0	0	1	7	15	39	69	79	26	3	0	0	0	0	0
50	0	0	0	0	0	0	0	3	8	25	72	150	121	43	12	1	0	0	0	0	0
55	0	0	0	0	0	0	0	0	4	39	84	115	71	15	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	2	5	21	24	11	0	1	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3-1
Graphical Form of a Joint Acceleration-Speed Probability Density Function (JASPROD)



3.4.1.3 Vehicle Characteristic Information

In addition to modal activity data, the MEASURE Aggregate Modal Model also requires vehicle fleet information. Emission rates are applicable to vehicle technology groups that are defined by such factors as model year range, fuel delivery technology, accrued vehicle mileage, and transmission type. Researchers collected vehicle license plate data to develop vehicle technology information. The capture of license plate data allows for the determination of the onroad vehicle composition at each ramp and on the mainline through a two-step process. License plate data were tied to vehicle identification numbers (VINs) in the Georgia Department of Revenue registration database. The VINs were decoded using proprietary software to develop the actual onroad distribution of various vehicle technologies. These technology distributions were then used to match with the vehicle characteristic variables present in the MEASURE model emissions algorithms. To protect privacy a double blind process was employed. Plate information was gathered, but can not be linked to individuals vehicles nor their owners names or addressees.

3.4.1.4 MEASURE Aggregate Modal Model analysis

As discussed above, vehicle technology and activity measures are combined with technology and modal-specific NOx emission rates to produce the estimates. The actual MEASURE Aggregate Modal Model analysis was performed on sets of binned vehicle modal activity data and not individual vehicle speed/acceleration traces. The data were binned and analyzed in 15-minute time slices by location and metered condition (i.e. ramp meters on or off). Each bin was then treated as independent data points for analysis and aggregated for summary purposes.

The emissions analysis was conducted at two levels. The first emissions analysis assessed changes in gram/second emissions rates under various operating and ramp metering conditions. The second emissions analysis examined the predicted mass emissions levels based on the emissions rates and the observed traffic volumes. Mass emissions are a function of gram/second emission rates multiplied by seconds of vehicle operation. Changes in travel demand result in changes in freeway and ramp volumes, changing mass emissions. Changes in average speeds also result in different mass emission levels, even if the emissions rates remain the same. That is, even if gram/second emission rates remain constant, mass emissions can increase when speeds drop, since vehicles spend more seconds of operation on then facility.

The emissions analysis considered variations from ramp location to ramp location, but the focus of the research was on the impact of the system on the local transportation corridor. Specifically, the analysis considered the impact of NOx emissions levels. The emissions estimates from the MEASURE Aggregate Modal Model are presented in Chapter 5.

3.4.2 MOBILE5b Emissions Analysis

Emissions estimates from the USEPA MOBILE5b model were produced and compared with the estimates from the MEASURE Aggregate Modal Model analysis. To the degree possible, the MOBILE5b emissions analysis conformed to the MEASURE procedures, so that easily comparable estimates were produced. The MOBILE models are intended for application to vehicles in the aggregate over the course of a complete trip (USEPA, 1992). This is one of the fundamental problems with using the MOBILE model for the evaluation of TCMs or other transportation improvements that only impact a portion of a trip. Indeed, one purpose of comparing the MOBILE analysis results with MEASURE Aggregate Modal Model estimate is to identify the specific drawbacks associated with using the trip based emissions rates in MOBILE for TCM analyses. This notwithstanding, every effort was made to use the highest level of aggregation and averaging to produce the most appropriate estimates from MOBILE5b.

All assumptions regarding fleet mix, fleet age, inspection maintenance programs, and reformulated fuels were the same as those used by the Georgia Department of Environmental Quality for the Atlanta conformity analysis for the year 1999. The regional fleet characteristics were used in comparisons so that the standard MOBILE5b control file used in Atlanta analysis could be employed (The MOBILE5b control files used for this analysis are presented in Appendix B). The MEASURE Aggregate Modal Model emissions rates were estimated using the modal activity data collected with laser guns in the field. The average speed data required to run MOBILE5b were derived from the same modal activity data.

The analysis was stratified by day, time, and location to match the analysis bins used for the assessment of the modal activity and MEASURE Aggregate Modal Model analysis. This allowed for a direct comparison of emissions estimates under varying conditions and ramp configurations. The comparison of the two modeling methods focused on the mass emission estimates as well as the emissions rates. Because the MOBILE5b emissions rates are in grams per mile and MEASURE Aggregate Modal Model emissions rates are in grams per second, the MOBILE5b rates were converted to grams per second units so that the two could be directly compared. The model comparison and result of the analysis are presented in Chapter 5.

3.4.3 Assessment of Ramp Design and Prevailing Traffic Conditions

In addition to the emissions analysis, this research also attempted to assess and identify the specific conditions that lead to vehicle modal activity on freeway onramps that potentially lead to elevated emissions levels. It is not enough to simply assess the emissions impact without investigating the specific cause for the changes. This portion of the research was designed to assess the traffic flow conditions and ramp design parameters that may contribute to higher emissions. This analysis focused on the assessment of vehicle modal activity changes under ramp metering conditions. Relevant operating mode variables from the emission rate models serve as the response variables for the analysis (Table 3-2 provides the modal variables tested).

Table 3-2
Modal Activity Description Variables

Variable	Measure
ACC3	Proportion of Activity with Acceleration >= 3.0 mph/s
ACC6	Proportion of Activity with Acceleration >= 6.0 mph/s
DEC2	Proportion of Activity with Deceleration <= -2.0 mph/s
ISP90	Proportion of Activity with IPS >= 90 mph^2/sec
ISP120	Proportion of Activity with IPS >= 120 mph^2/sec
AVESPEED	Average Vehicle Speed (mph)

Because the detailed statistical analysis performed for the development of the MEASURE Aggregate Modal Model algorithms has shown that these variables are related to vehicle emissions, they have been chosen for use in this analysis (Fomunung, 1999). Using a variety of variables as measures of change in modal activity allows for a complete assessment of activity variations.

Numerous factors potentially influence vehicle modal activity. This research identified many factors and based on the their relation to freeway and onramp operations and the availability of data, chose several to function as the independent variables for this analysis. It was not practical to assess all factors that potentially influence modal activity; therefore, this analysis focused on variables that are related to the operation and installation of ramp meters (HCM, 1998). Specifically, these include mainline flow rates, and ramp design elements. Several different flow variables where chosen along with geometric design variables such as grade and acceleration distance. The independent variables used in this analysis are listed in Table 3-3.

Ramp meters are intended to allow for a smooth transition of vehicles between the arterial system and the freeway system. This transition is typically not problematic during light or uncongested traffic levels. Thus, ramp meters are not needed under these conditions. The use of ramp meters during uncongested traffic conditions results in delays to vehicles on the onramp with little or no benefit to the mainline traffic flow. Thus, DOTs typically reserve ramp meter operations for congested peak period conditions. It is during these conditions that gaps between vehicles decline and merging becomes more difficult. The critical factor in this is the prevailing mainline traffic conditions; therefore this research was concerned with how modal activity changes as traffic volume changes at the merge area. As the ability to merge becomes more difficult for drivers, vehicle acceleration behavior also changes. The goal is to isolate these changes and identify any consistent patterns that indicate when operating ramp meters significantly increases emissions. To accomplish this, several different traffic flow measures were also selected for analysis, see Table 3-3.

Table 3-3
Modal Activity Analysis Independent Variables

Variable	Measure
LOS	Mainline Level of Service at Onramp Merge Area, (A,B,C,D,E, or F)
Flow Rate	Mainline Flow Rate at Onramp Merge Area, (Passenger Car Equivalent per Lane per 15-min)
Lane 1&2 Flow Rate	Mainline Flow Rate for Lane 1 and 2 Only, at Onramp Merge Area, (Passenger Car Equivalent per Lane per 15-min)
Forced Flow	Forced Flow/Free Flow Conditions on Mainline, (Forced Flow Defined as Average Mainline Speed Less than 50 mph)
Percent Trucks Ramps	Percentage of Trucks in the Ramp Traffic Mix
Percent Trucks Mainline	Percentage of Truck in the Mainline Traffic Mix
Grade	Onramp Grade (Percent)
Acceleration Distribution	Onramp Acceleration Distance (Distance from Stop Bar to End of Gore)
Ramp Design	Onramp Configuration (Parclo or Diamond)

Using Level of Service (LOS) as a measure of traffic level allows varying flow rates to be classified in groups to simplify analysis. Conversely, using the actual flow rate allowed for the analysis with the traffic condition as a continuous variable. In addition, conditions were assessed as either free flow or forced flow, using probe vehicle speed to identify the conditions. It was anticipated that the observed mainline conditions might not provide a wide spectrum of LOS for a comprehensive analysis. Thus, a simplified classification focusing on the critical traffic breakdown condition was included. Researchers also speculated that vehicles merging from the ramps would be influenced most by the vehicles in the immediately adjacent traffic lanes. To test this, the flow for the first two traffic lanes was analyzed separately. For this analysis, all traffic flow measures were converted to passenger car equivalents. To assess traffic mix impacts on the onramp and mainline, truck percentages were evaluated for their impact on modal activity.

All of the other variables assessed for this analysis were related to the ramp geometric design. In addition to impact of traffic flow on modal activity, it was also assumed that the design of the onramp would have an influence (Sullivan, 1993). The design features considered most important were grade, acceleration distance, and interchange design. Grade was measured as percent, acceleration distance measured in feet from the ramp meter stop bar to the end of the gore, and ramp designs elements included two designs: diamond and partial cloverleaf (parclo).

Other factors such as weather conditions, pavement conditions, driver characteristics, and vehicle type also have a potential influence on modal activity. These factors were either held constant or were not included in analyses due to data limitations (analyses were limited to modal activity of passenger vehicles and the data collection was limited to dry daylight conditions). These data were also collected during the evening peak period when most activity is associated with work commute trips. Thus, the influences of external factors, such as those listed above, were assumed to minimized by the data collection criteria and analysis conditions.

3.4.3.1 Statistical Analysis

The relevant operating mode variables from the emission rate models served as the response variables for the statistical analysis. Each variable was tested for influence on modal variables using the t-test, allowing for hypotheses testing to determine if two observed sample means are likely from the same populations (Neter et al., 1996). For this research, the null hypothesis was that two sample populations were not likely from the same population. If the average proportion of activity greater than 3 mph/sec under forced flow conditions appears to be from a different population than under free flow conditions, the t-test indicates that forced flow conditions is a likely influence on modal activity. If this test were conducted at the 95 percent confidence level, the conclusion would be that the difference in the sample means would only occur from the same population five percent of the time. Thus, one could conclude that it is likely that the means are from separate populations, but it is not absolute. Nonetheless, this allows for reasonable conclusions about which variable influence modal activity on freeway onramps. The findings of the analysis of the modal activity using the t-teat are presented in Chapter 5.

3.5 Research Limitations

The goal of this research is to provide conclusions regarding the potential air quality impacts of ramp metering systems through the collection and analysis of modal vehicle activity of a ramp metering system under metered and non-metered conditions. The approach presented in this chapter provides an original and innovative method for drawing conclusions about the impacts of ramp metering systems that significantly add to the current base of knowledge. This notwithstanding, there are some limitations within this research that should be considered.

First, the emissions estimates are the product of a modeling exercise. As with all modeling work, conclusions based upon model results are only as accurate as the models that are applied in the analyses. Modeling assumptions can limit the applicability of the models to specific problems and can affect the accuracy of model results. The MEASURE Aggregate Modal Model takes into consideration numerous factors that influence vehicle emissions rates. This model is a new tool developed for modeling vehicle emissions from a disaggregate perspective. Validation work indicates that the MEASURE Aggregate Modal Model provides more accurate exhaust emissions estimates for those light-duty vehicles that were included in the validation study (Fomunung, et al., 1999). MEASURE Aggregate Modal Model modeling results are compared with those of MOBILE5b before drawing conclusions. However, model validation work is ongoing. Significant model improvements may be forthcoming that could change the predicted emission rate impacts of metering. As they are developed, alternative model formulations should be tested with the data that were collected in this study. One of the tremendous advantages provided by the research was the comprehensive modal activity database that can be used to examine the predictions of future emissions model formulations.

All efforts were made to gather accurate, comprehensive, and unbiased data. Indeed this has been accomplished to the highest degree possible, but with the project time and resource constraints, some gaps in the data did occur. Procedures were developed to account for missing data or small sample sizes. Consequently, the confidence associated with some data subsets is higher than for others. Where data limitations occur they are identified, accounted for in the analysis, and noted during the presentation of results. The data are therefore presented in varying levels of detail to provide for a comprehensive assessment of an aggregate level and a detailed assessment where warranted.

Finally, this is an empirical assessment of the modal activity associated with a specific ramp metering system in Atlanta over a two-month period. The intent is to provide a data set that can be used to draw general conclusions about ramp metering systems. The transfer of the data and conclusions to other areas should be conducted with caution. This system is the only ramp metered freeway section in Atlanta and is not necessarily representative of the most congested freeway sections in the city. Hence, even though the researchers conclude that ramp meter implementation on corridors such as the one investigated provide no air quality benefit, there may be other corridors in the city that could benefit from ramp meter implementation. This issue is discussed in more detail later in the report.

Atlanta drivers have been noted to behave differently than those on other metropolitan areas (Ross, et al., 1995). Variations in travel demand and driver behavior occur from region to region and over time, potentially limiting the transferability of the conclusions presented in this report. In brief, the research conducted in Atlanta provides significant methodological improvements and data that can help researchers draw more universal conclusions about the air quality impacts of ramp metering systems. The findings of the study should be used in conjunction with additional data, as they become available. Nevertheless, the research results from the Atlanta study provide important findings related to the implementation of ramp metering systems and also provides useful procedures for evaluating other TCMs.

3.6 Contributions of Research

This work provides a detailed modal activity assessment and emissions impact analysis for the Atlanta ramp metering system. The research also provides analytical methods that can be applied to the evaluation of other TCMs. One goal was to develop a detailed and comprehensive data set unlike any that has been collected in the past, providing new and meaningful information. A second goal was to develop an underlying research methodology that contributes to and improves upon current analysis procedures in this area. The research was designed to improve on past ramp metering studies by examining a ramp meter system (ramps and concurrent mainline activity). By utilizing a modal modeling approach, researchers were able to examine the impact of ramp design and traffic conditions (LOS) on the vehicle modal activity, emissions rates, and net system emissions.

CHAPTER 4
RESEARCH PROCEDURES

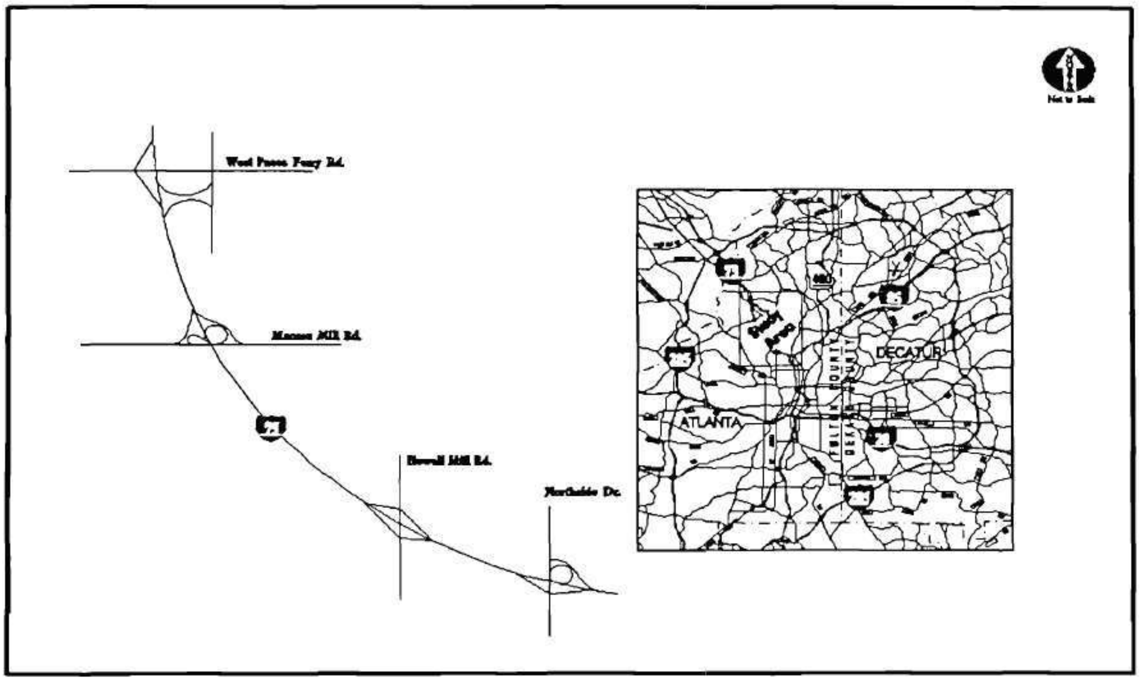
To evaluate the air quality impacts of a ramp metering system using modal modeling approaches, it is necessary to collect actual modal activity data from vehicles operating on the roadway. Empirical information was required to understand system impacts and to provide data for use in average speed and modal emissions analysis. Because this research was concerned with traffic flow impacts, as well as air quality implications, both traffic flow and modal activity data were required for performing a complete evaluation of a ramp metering system. In addition, ramp metering systems are designed to improve mainline traffic flow and therefore inherently impact both onramp and mainline vehicle operations and instantaneous speed/acceleration profiles. It was therefore necessary to design a data collection strategy that included operational and environmental information for the onramp and mainline sections of the ramp metering system. It was also important to evaluate the impacts on a system-wide basis and not simply on a ramp or interchange basis. With this in mind, the data collection effort was designed to include the simultaneous collection of ramp and mainline freeway data to account for interactions and fluctuations in the system that might otherwise be overlooked.

On the operations side of the data collection effort, data collection focused on the detailed monitoring of the traffic flow conditions along the ramp metering system. This included traffic counts of the mainline, the ramps, and the adjacent arterial system. To model the environmental impacts of the system, instantaneous modal activity information was needed for vehicles on the mainline sections of the system and on the onramps, as well as classification and technological information for vehicles operating in the system.

4.1 Data Collection Sites

The I-75 corridor, immediately north of the Atlanta central business district, was selected as the study site for this research. This section of freeway on the northbound I-75 corridor, just north of the I-75/I-85 downtown connector, contains all five of Atlanta, Georgia's ramps currently equipped with ramp meters. Laser guns and other data collection equipment were employed to collect vehicle operations and activity data on the first four of these five ramps, and the mainline sections of the system. The fifth ramp, separated from the other ramps by approximately 1 mile, was excluded from the data collection plan, because downstream construction activity during the data collection period was predicted to impact the activity in the study area. The field team, however, did collect vehicle classification information and analyze remote sensing emissions data at this ramp. The research team collected vehicle activity data from the four-ramp system (see Figure 4-1) for 18 days during the spring of 1999

Figure 4-1
Study Area Location Map and Interchanges



4.1.1 Onramp Locations

The four ramps that were included were the first four in the system as shown in Figure 4-1. The four ramps included the onramps from: Northside Drive onramp, which is the first access point on I-75 northbound after it splits from I-85; Howell Mill Road; Moores Mill Road; and West Paces Ferry. The Georgia DOT retrofitted all five ramps with ramp meters. The four ramps in the study area include different geometric designs and configurations allowing for the evaluation of the impact of alternate ramp design on operations and modal activity.

- The Northside Drive ramp is a loop ramp on a negative grade (ranging from -2 to -4 percent) connected to an auxiliary lane that is also connected to the Howell Mill Road exit ramp 700 feet downstream.
- The Howell Mill Road ramp is a short ramp (1000 feet), which is similar to the Northside Drive ramp, is also on a negative grade (ranging from -2 to -7 percent). This ramp is part of an urban diamond interchange and has a strait horizontal alignment until it reached the gore area and merges with the curved alignment of I-75 northbound.
- The Moores Mill Road onramp is part of a partial cloverleaf interchange (Parclo). It has a slight curved horizontal alignment, although it is straight from the ramp meter stop bar to the merge area, and is on a positive grade (+3 percent). This ramp is the only ramp that is connected to the arterial system at a non-signalized intersection. As

this would indicate, this ramp also carried the lowest traffic volume of the four study area ramps.

- The West Paces Ferry onramp is a 1700 foot curved ramp on a positive grade (ranging from 2 to 5 percent). This ramp is characterized as having the longest acceleration distance (820 feet from ramp meter stop bare to the end of gore) of all study area onramps. This ramp is the final and furthest north of the ramps in the study area system.

The following Table 4-1 includes a summary of the design and alignment characteristics of each of the four study area onramps.

Table 4-1
Geometric Design Characteristics for the Study Area Onramp Data Collection Locations

LOCATION	Grade	Ramp Length (feet)	Acceleration Distance (feet)*	Interchange Design	Loop Ramp	Presence of Auxiliary Lane
Northside Drive Ramp	-4 to -2	1080	550	Parclo	Yes	Yes
Howell Mill Road Ramp	-7 to -2	975	450	Diamond	No	No
Moores Mill Road Ramp	-1 to +3	2000	700	Parclo	No	No
West Paces Ferry Road Ramp	+2 to +5	2000	820	Parclo	Yes	No

*** Stop bar to end of gore**

4.1.2 Mainline Locations

The focus of this study was not limited to the onramp locations. A critical component of this study was to assess the impact of the vehicle activity on the freeway mainline. This research required the collection vehicle operations, modal activity, and classification data for mainline conditions. The study area included a 4.4-mile section of freeway. This section is comprised of one 700-foot weave area between the Northside Drive onramp and the Howell Mill Road off-ramp, three merge areas, and remaining 3.6 miles of basic freeway section. Four primary locations within the study area were chosen for collecting mainline data. The freeway overpasses within the study area were used as the locations for such data collection.

The Northside Drive overpass was used as the primary location for collecting mainline traffic volumes data, and was also used for collecting modal activity data. The Howell Mill Road overpass was also used as a location for collecting vehicle activity data. The Peachtree Battle Road overpass (non-interchange) located between the Howell Mill Road interchange and the Moores Mill Road interchange, was used as a third location for collecting vehicle activity data.

Finally, the Moores Mill Road overpass was used as a location to sample vehicle classification and sub-fleet mix information.

4.2 Data Collection Equipment

To gather and store the large amounts of vehicle data needed for this research, several instruments were used in data collection. Vehicle counts were collected primarily through the use of video cameras, although Nu-Metric detectors placed on roadway and manual counting devices were also implemented during the data collection process. Instantaneous vehicle speed/acceleration profiles were collected on the ramps and mainline primarily through the use of laser guns, with supplemental data coming from probe vehicles, equipped with distance measuring instruments (DMIs).

4.2.1 Laser Rangefinders

The laser gun units used to collect vehicle modal activity for this project were the Advantage laser rangefinder (LRF) manufactured by Laser Atlanta Optics. The LRF units are portable, hand-held devices that measure the distance to an object at a high sampling frequency (238.4 distance measurements per second) with a manufacturer's accuracy specification of six inches. Seven laser guns, mounted on tripods for stability, were used for the collection speed profile data for this project. The LRF, or "laser gun" contains an internal algorithm, which can convert the range readings into speeds or merely download every distance measured. The latter was the mode used for this project as it provided the most detailed and disaggregate level of output. When speed data are aggregated by the LRF automatically, researchers lose important and descriptive data points. Collecting the high-frequency distance data directly from the LRF provided a more complete dataset, but required the processing of the output to calculate speed and acceleration rates. The important properties of lasers that allow for measurement of modal activity of vehicles are the wavelength, duration of emission of light, beam divergence, and coherence (Grant, 1999).

Procedural setup, operation, data collection, and data storage at the site using the Advantage LRF is discussed in the following section. Data post processing, analysis, and field findings are discussed Chapter 5.

4.2.1.1 Wavelength and Frequency

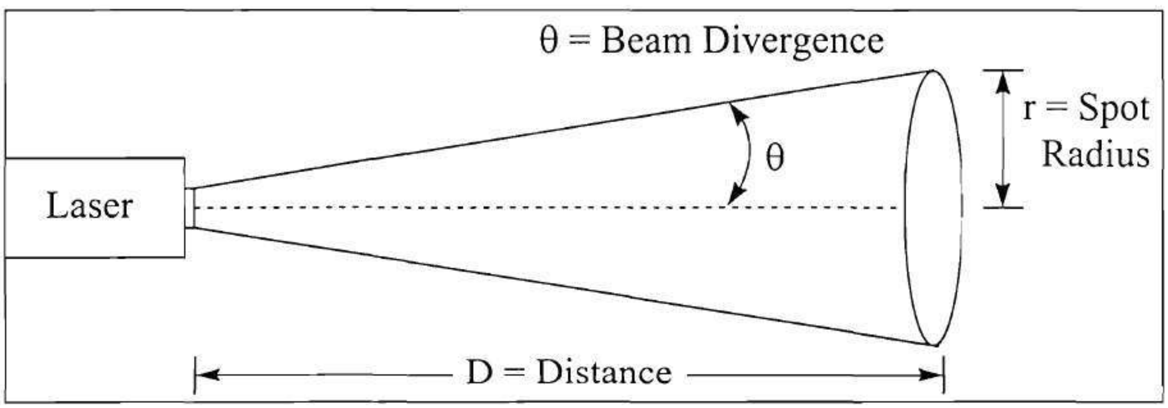
Wavelength is a fundamental characteristic of light, and each type of laser emits light with a known characteristic wavelength. The value of the wavelength is dependent upon the type of material that emits the laser light, the optical system, and how the light is energized. The wavelengths for most lasers is a range of values, but the range is so narrow that for most purposes it appears to be a single wavelength (Hecht, 1992). Specifications on the Advantage laser rangefinders are a wavelength in the infrared range of 850-950 nm (Laser Atlanta, 1997).

The wavelength of light is a convenient unit for measuring distances. The same principle of radar measurement of distance is used in calculating distances with lasers. An object is targeted with the laser, then a short pulse of light fires from the laser. The time it takes the reflected light to return to the unit is measured by the receiving lens every 35 nanoseconds. Distance is divided by two because the light actually travels twice the distance to the target (to the target and back to the receiver). Post-processing of the binary data divides the binary range into a distance of the vehicle from the laser unit. This information was then stored in files on PCMCIA cards inserted into the Advantage LRF unit.

4.2.1.2 Divergence

The laser beam expands as it travels further from the source (Figure 4-2). This spreading is called divergence, and is typically measured in milliradians. Once a sufficient distance from laser, multiplying the sine of the divergence angle (which equals the value of the angle for small angles measured in radians) by the distance the beam has traveled results in the spot radius of the laser (Hecht, 1992).

Figure 4-2
Laser Rangefinder Beam Divergence



Manufacturer specifications on the Advantage are a divergence of 3 milliradians. Thus, after the beam has traveled 100 feet its diameter is 0.6 feet, or 6 feet after traveling 1000 feet. This is the average distance an automobile can be tracked under congested conditions. For heavy-duty vehicles, the rear of the trailer provides a very large surface from which the laser can range. At 2000 feet, the beam of the laser would be 12 feet in diameter, slightly larger than the width of the trailer unit. In sampling with the hand-held laser unit, it is not uncommon to track heavy-duty vehicles for distances twice as long as automobiles at the same location (Grant, 1999). Table 4-2 provides radius/diameter of the LRF beam at various distances from the unit.

Table 4-2
Laser Rangefinder Beam Radius and Diameter Readings

Distance (feet)	Spot Radius (feet)	Diameter (feet)
100	0.3	0.6
500	1.5	3.0
1000	3.0	6.0
1500	4.5	9.0
2000	6.0	12.0
2500	7.5	15.0

Divergence of the laser beam places limitations on the LRF to track long distances. Surrounding traffic must not impede the path of the beam. As congestion increases, spacing between vehicles decreases, reducing the distance in which the laser is able to track vehicles before interference from surrounding traffic. Observation of the traces show more seconds of activity under congested regimes due to slower vehicle speeds, but the distance of measurement is less than under free-flow conditions.

Small divergence of the laser units is important for sending the beam distances up to 2500 feet for non-reflectorized distance measurement. High directionality of the beam is an important property allowing the laser to tracking one particular vehicle in a stream of vehicles. Typical radar guns use the Doppler effect of waves to measure the speed of the object. With multiple moving objects in the field of view of a radar gun, the exact object moving cannot be determined precisely. Directionality of laser beams allows use of the heads-up display (HUD) to "aim" the beam at a particular vehicle in the stream and track it as it moves through traffic. A distinction can then be made as to the type of vehicle (i.e. auto vs. 2-axle 6-tire, etc.) belonging to the data collected and where the vehicle was located with respect to the surrounding traffic (e.g. lane number).

4.2.1.3 Distance Uncertainty

Some lasers emit steady beams of light while others emit pulses that can vary in duration and frequency of occurrence. The Advantage emits pulses of laser light to measure distances to objects. The laser pulses beams at high frequency toward an object to measure the location of the object hundreds of times a second. The Advantage emits pulses of laser light at a frequency of 238.4 hertz (238.4 range readings per second). The pulse of the laser should be short for measuring distance accurately using just the return of the beam. Uncertainty in distance measurements can be computed from the formula relating the speed of light and the pulse duration. Reducing the pulse length will reduce the distance uncertainty in laser rangefinders. However, in practice, the uncertainty is strongly affected by the accuracy of pulse-timing and measurement electronics (Hecht, 1992; Landry, 1997).

The pulse duration for the handheld lasers is 35 nanoseconds, with 238.4 pulses occurring over a one-second time period. Given the constant speed of light, the 35-nanosecond pulse equates to each pulse of laser light being approximately 35 feet in length. This ray of light is sent out to the object, and bounced back to the laser unit and received by the lens. The LRF reads the returns and develops the mean time of the beam.

The distance uncertainty is equal to the speed of light constant ($3*10^5$ km/sec) multiplied by the pulse duration ($35*10^{-9}$ sec) divided by 2. This gives an uncertainty of 0.00525 km, only taking into account pulse length. The uncertainty is further reduced in the handheld lasers by varying the time in which the window is open for measuring the laser light, and primarily by measuring the intensity of the returned light to develop the mean travel time of the beam of light.

The time for which the laser unit is open to receive light is a function of the mode of operation. For first return mode, the time "window" in which the laser will range is 4 microseconds, while in last return mode the time is 100 microseconds. The unit measures the energy of the returned light. Based on the intensity, time, and mode of operation, a distance is computed which reduces the measurement errors in the unit.

First return and last return mode operate by differentiating return sequences with 35 or more feet separation. The LRF unit has trouble when two objects in the line of the beam are closer than 35 feet to each other. When this occurs, the LRF has difficulty measuring distance to an object and most likely will be the average of the two distances (Landry, 1997). However, when the two objects are separated by 35 or more feet, two distinct range readings will be observed by the LRF, and the range returned will depend on mode (first or last) programmed on the gun.

During the data collection process of this project, the LRF units were used in both first and last return. The first return programming provides the most consistent distance readings, but as discussed above, it was not always practical to operate the units under this program. When collecting data from locations with obstructions, such as a cyclone fence, it was necessary to operate the LRF units with the last return program. If the laser beam is partially broken by an obstruction the last return program provides for unit to disregard the beam return form the obstruction. When collecting vehicle traces from an overpass the last return program was used because there was a fence between the LRF unit and the target vehicles.

Several corrections have to be made for accurate distance measurement. The unit needs to be operated within an appropriate temperature range. The Advantage laser guns use an internal thermometer to gauge the outside temperature. The LRF should only be operated under dry conditions for the best results. In addition, the time from beam return time has to be adjusted for the time of the internal circuitry. All of the adjustments are made by the internal mechanisms of the laser before computing a distance of every reading (Landry, 1997).

4.2.2 Probe Vehicles

Although the Advantage LRF units were the primary means used to collect vehicle speed/acceleration profile information, probe vehicles equipped with DMIs were used to collect supplemental information. The DMIs were used to record second-by-second vehicle distance, speed and acceleration information. The DMI equipped probe vehicles were primarily used for two functions that the LRFs were not able perform. Probe vehicles collected vehicle traces along the complete mainline section of the ramp metering system study area (i.e. over four miles). As discussed above, the LRF units operating from a stationary position are only able to track vehicles for up to 1000 feet. The Probe vehicles allowed for the collection of a limited number of traces over the entire freeway section.

The probe vehicles were also used to collect vehicle modal activity data through curved sections of the onramps in the study. For the LRF units to operate effectively, they need to be positioned as to track vehicles in a straight-line trajectory. Probe vehicles allowed for the collection of data in areas of the system where this was not possible. The two locations were this was most critical were the curved sections of the Northside Drive and West Paces Ferry onramp locations. The DMI equipped probe vehicles were effective in collecting data under the above-described circumstance, although the amount of data collected was far less than that which could be gathered through the use of the Advantage LRFs.

Distance Measuring Instruments (DMIs) are typically used in floating car or probe vehicle studies of highway and arterial speeds across the United States. DMI sensors are attached to the transmission of the probe vehicle. By monitoring the number of electronic pulses received, the DMI measures the number of drive shaft rotations. Each drive shaft rotation is converted into distance traveled as a function of the differential gear ratio and tire diameter. Each pulse typically represents less than 1 foot of travel.

The DMI employed for this project was the Nu-metrics Nitestare NS-60. The NS-60 is calibrated to each individual vehicle depending on the pulse rate and the disk revolution rate. The accuracy of the data from the NS-60 is only as precise as the calibration process. The South Fulton County Airport runway was used as the probe vehicle calibration course (1000-foot calibration distance with minimal grade changes and that was free of curves). Note, however, that DMI accuracy can fluctuate as a function of tire inflation (which changes the tire diameter and distance traveled per drive shaft rotation). Hence, the accuracy of the DMI unit can change across days or even during the day as a function of tire temperature. However, the acceleration (relative change in velocity) tends to retain accuracy as temperatures change.

Once the NS-60 units were installed and calibrated, they were ready for data collection. For the purposes of this study, a BASIC program downloads and stores second-by-second speed and distance information from the NS-60 to a laptop computer operated by a data collector riding in the probe vehicle. Data from each run was then stored to an individual file, downloaded, and cataloged in the lab at the end of the data collection session. The data collectors were also supplied with a log sheet and were required to manually record information related to each data run, including the data file name.

Two vehicles were equipped with DMIs during the data collection phase of this project. One of the vehicles was a 1993 Dodge Spirit and the other was a 1992 Ford Tempo.

4.3 Data Collection Process

The data collection period was spread over several months during the spring and summer of 1999, with the highest concentration of data collection occurring during a two-month period in the spring. Data collection was conducted in the spring to take advantage of the best weather, while also ensuring for typical traffic conditions and travel patterns. As called for in the original data collection plan, a total 18 days of comprehensive data collection (i.e. concurrent monitoring at all locations) were performed. This was supplemented by partial data collection deployments during the summer months to collect additional data. During the most intense data collection period, up to 15 data collection personnel were deployed in the field on a given day.

The ramp metering system on I-75 northbound in Atlanta only operates during the evening peak period from 3:15 p.m. to 6:30 p.m. Therefore, the collection of vehicle activity for this project was centered on that same period. Data were collected on weekdays only. Of the 18 data collection days, five occurred on Mondays, while only two occurred on Fridays. Table 4-3 summarizes the days on which data were collected and the number of data collection days for each day of the week.

Table 4-3
Core Data Collection Activity Summarized by Day of Week

Day of Week	Number of Data Collection Days	Dates Data Collection was Performed
Monday	Five	May 3, 10, 17, 24, & June 7
Tuesday	Four	May 4, 11, 25, & July 27
Wednesday	Four	May 12, 19, June 4, & 9
Thursday	Three	May 20, 27, & June 10
Friday	Two	May 28, & June 4
Total	**Eighteen**	**May 4 to July 27**

Data collection was performed under dry weather conditions only. Although the LRFs are durable units designed for field use, it was recommended that they not be used in the rain. Therefore, the LRF units were not deployed under any threat of inclement weather. Data collection deployment occurred early enough in the afternoon to allow for all data collection equipment and personnel to be in place and ready by 3:15 p.m. on a given data collection day. Data collection efforts were terminated at 7:00 p.m. each day in order to cover the complete peak travel period.

4.3.1 Data Collection Personnel

In total, 25 Georgia Institute of Technology undergraduate students were hired to assist with the data collection process. Students were primarily employed to operate the seven Advantage LRFs designed to gather instantaneous vehicle speed/acceleration profiles on the Atlanta ramp metering system. These students were supervised in the field by senior research staff. To gather quality data in a safe and efficient manner, field personnel were put through a multi stage training routine. The training schedule included project orientation, equipment training, safety procedures, and trial data collection deployment.

All student workers were hired and introduced to the project during the first week of April 1999. Student data collectors were hired for the entire spring quarter, which ran from March 30 to June 11, 1999. This coincided with the planned data collection period and was convenient for the students. Due to daylight limitations, data collection efforts that required deployment until 7:00 p.m. could not take place until after daylight savings time, which did not start until April 4, 1999. Equipment training and orientation was conducted within the two weeks following the project introduction meeting. Students were identified for a specific task early in the training sessions based on their background and availability. They were then assigned to a deployment location and trained based on the requirements of that location. That is, only those scheduled to work with the LRFs were allowed to use to the units, while others were trained on the probe vehicles or other data collection equipment. After the initial equipment training session, the students were deployed in the field for test data collection sessions. Before actual data collection was initiated on May 3, 1999, two "dry" runs were conducted on April 21 and 27, 1999.

Before any students were deployed in the field in any capacity they were required to participate in a safety orientation. All data collectors were briefed on the safety concerns for this type of fieldwork and required to follow the following restrictions:

- At no time is a person allowed to enter an active travel way
- Each person will be dropped-off and picked-up at their designated data collections site by the research project shuttle
- Personnel must exit the shuttle on the side of the vehicle that is not adjacent to traffic
- At no time shall anyone leave their designated location without permission from a research supervisor
- Each person should be alert to arrant vehicles and avoid turning their back completely to traffic
- Personnel shall not interfere with existing traffic patterns or take any activity (other than those required for data collection efforts) that may distract drivers or alter driving conditions
- Stay as far from the active travel way as possible
- Do not alter traffic control devices that have been placed at the data collection sites intended to enhance safety.
- All persons must adhere to the dress code, which includes safety vest, hardhat, and long pants.
- Teams of two or three must conduct data collection performed in a vehicle. The drivers of the vehicles are not allowed to perform any activity other than operating the vehicle.

To assure safe and proficient data collection, data collection personnel were provided with a field manual. This handbook included detailed data collection instructions for all tasks, and operating and safety procedures. A copy of this manual is provided in Appendix C. The data collection personnel were mainly involved in the collection of vehicle speed profiles, but were also used to operate probe vehicles and collect vehicle traffic counts.

4.3.2 Collection of Vehicle Modal Activity Data

Vehicle modal activity data, such as speed/acceleration profiles, were collected on all four study area freeway onramps and the entire 4.4-mile study area mainline section. The Advantage LRFs and instrumented probe vehicles were used to collect the vehicle modal activity data. Seven LRFs and two probe vehicles were used in data collection. Equipment and field deployment tests started during the end of April, with full deployment commencing in May of 1999.

Once the change to daylight savings time occurred in April, sufficient light was available to allow data collection activities until the required 7:00 p.m. time period. The collection of the vehicle modal activity data was to be centered in the p.m. peak period, when the ramp meters were in operation. The data collection activities were carried out for approximately four hours per session from 3:15 p.m. to 7:00 p.m. on a typical day. Eighteen days of comprehensive data (i.e. collection of data at all ramps and the mainline simultaneously) and five days of partial data (i.e. one or two locations) were collected during the months of May, June, and July of 1999. The most intensive data collection efforts occurred between, May 3 and June 10, 1999, with seventeen days of full deployment (i.e. six to seven LRFs) taking place during that period. During four of these days, the ramp meters were turned off for the entire peak period. The five additional partial deployments and one full deployment occurred during the end of June and July to provide supplemental data to the core data collected in May and the beginning of June.

4.3.2.1 Laser Rangefinder Deployment

Advantage LRFs were deployed at eight different northbound onramp and overpass locations in the study area in order to gather appropriate vehicle modal activity data. The LRFs were mounted on tri-pods during data collection. LRFs were positioned on the Northside Drive, Howell Mill Road, and Peachtree Battle Road overpasses to capture mainline vehicle activity. Five LRFs were positioned on all onramp locations in the study area to capture ramp activity. This included one on the Northside Drive onramp, two on the Howell Mill Road onramp, two on the Moores Mill Road onramp, and one on the West Paces Ferry Road onramp.

It was not possible, nor practical, to trace each vehicle that passed each of the LRF locations. Therefore, each location had a sampling routine designed to gather activity data from a sample of vehicles from each site. The data collectors on the onramps were simply instructed to track every fourth vehicle that passed their location. This provided a representative sample of vehicle activity. A similar system was used for the mainline locations, but since the traffic volume did not allow for counting all vehicles, the data collectors were instructed to track every fourth vehicle after their attention had returned to the LRF HUD. Each sampled vehicle was classified by vehicle type based on the Federal Highway Administration (FHWA) 13-vehicle classification scheme. This study was primarily concerned with typical passenger cars and sports utility vehicles (SUVs). Vehicle classification was tracked through the use of a handheld JAMAR board electronic counter. This information was matched back to the vehicle trace during the data processing phase of the project (Grant, 1997b).

It would have been possible to gather information at a faster rate then every fourth vehicle, but because data collectors also completed a log sheet for data quality assurance, the sampling rate had to be slowed. In addition, data collection sessions were over four hours long and thus, data collection pace was an important consideration for data collector fatigue. A reasonable data collection pace provided for consistent data quality throughout the complete data collection session. Detailed data collector instructions for LRF operations, sampling procedures, vehicle classification routine, and a sample log sheets are provided in the data collection manual shown in Appendix C.

Two LRFs were rotated between the three overpass locations during the data collection period. The Peachtree Battle Road and Howell Mill Road locations were used extensively to capture mainline activity as they provided the most advantageous sites for tracking vehicles. The Howell Mill road location recorded vehicle mainline activity in the merge area while Peachtree Battle location captures activity on the basic section between the Howell Mill road interchange and the Moores Mill Road interchange. The Northside Drive location was used to a lesser degree to capture weaving and vehicle activity (i.e. on the Northside Drive onramp and Howell Mill Road off ramp weave section). Approximately 8,000 mainline vehicle traces were collected from these three locations.

The remaining five LRFs were deployed at the four ramp locations. The Northside Drive LRF was positioned behind the barrier wall immediately behind the stop bar for the ramp meter. This LRF captured vehicle activity from the stop bar to the merge area and weave section with the Howell Mill Road off-ramp. A LRF was placed at this location for 17 days during the data collection period recording approximately 68 hours of vehicle activity. Roughly 4,000 vehicles were tracked during this period at this site.

Two LRFs were deployed at the Howell Mill location, one for 18 days and the other for 17 days during the core of the data collection effort. One LRF was placed at the top of the ramp recording activity of vehicles as they approach the ramp meter stop bar. The other LRF was placed just upstream of the ramp meter and recorded vehicle activity from the stop bar through the merge with I-75 northbound. Over 3,800 vehicles were tracked at each of these locations.

One LRF was positioned at the Moores Mill Road onramp approximately 100 feet behind the ramp meter. Twenty days of vehicle activity data were collected at this position from the ramp meter stop bar to the I-75 merge section. Approximately 4,600 vehicle traces were recorded at this location. For one day during the data collection period, a LRF was placed at the head of the Moores Mill Road Ramp in order to collect data as vehicles approached the meter stop bar. Over 300 vehicles were traced on that day.

The West Paces Ferry Road onramp was the final location for the positioning of an LRF. This LRF was placed in advance of the ramp meter due to physical limitations of the site. The position recorded vehicle activity from approximately 50-75 feet from the stop bar through the merge section with I-75 northbound. Almost 4,000 vehicle traces were recorded at this location.

The LRF activity data collected from all nine locations is summarized in Table 4-4. Figures 4-3 to 4-6 illustrate the mainline freeway and onramp LRF data collection locations.

Table 4-4
Laser Rangefinder Data Collection Summary by Location

LOCATION	Total Days of Data Collection	Days of Data Collection With Metes Off	Total Hours of Data	Number of Usable Vehicle traces
Northside Drive Ramp	17	4	68	3926
Howell Mill Road Ramp	17	4	68	3268
Howell Mill Road Ramp, Advanced	18	4	72	3733
Moores Mill Road Ramp	20	4	80	4426
Moores Mill Road Ramp, Approach	1	0	4	307
West Paces Ferry Road Ramp	18	6	72	3189
Northside Drive Overpass	4	1	16	804
Howell Mill Road Overpass	15	3	60	3584
Peachtree Battle Road Overpass	· 11	3	44	2790
TOTAL	**121**	**31**	**484**	**26,027**

Figure 4-3
Laser Rangefinder Data and Video Data Collection Locations - Northside Drive

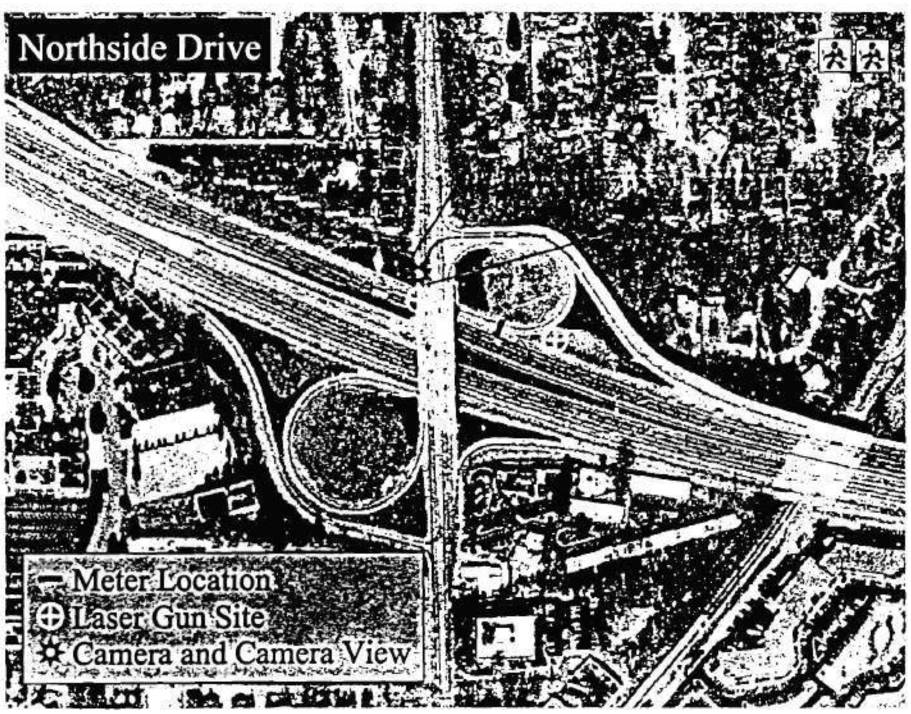


Figure 4-4
Laser Rangefinder Data and Video Data Collection Locations – Howell Mill Road

Figure 4-5
Laser Rangefinder Data and Video Data Collection Locations – Moore's Mill Road

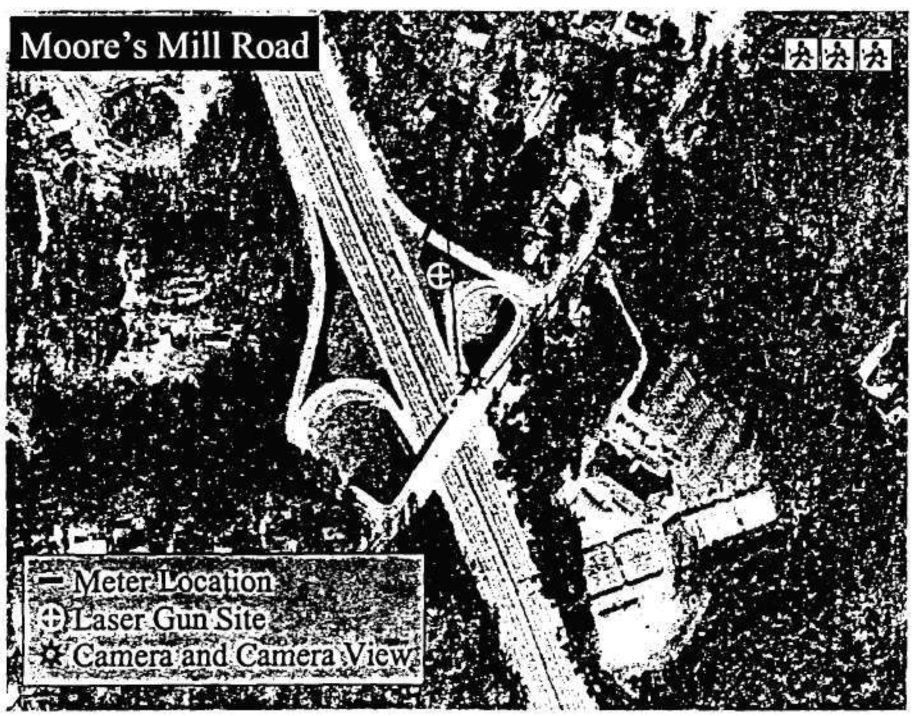
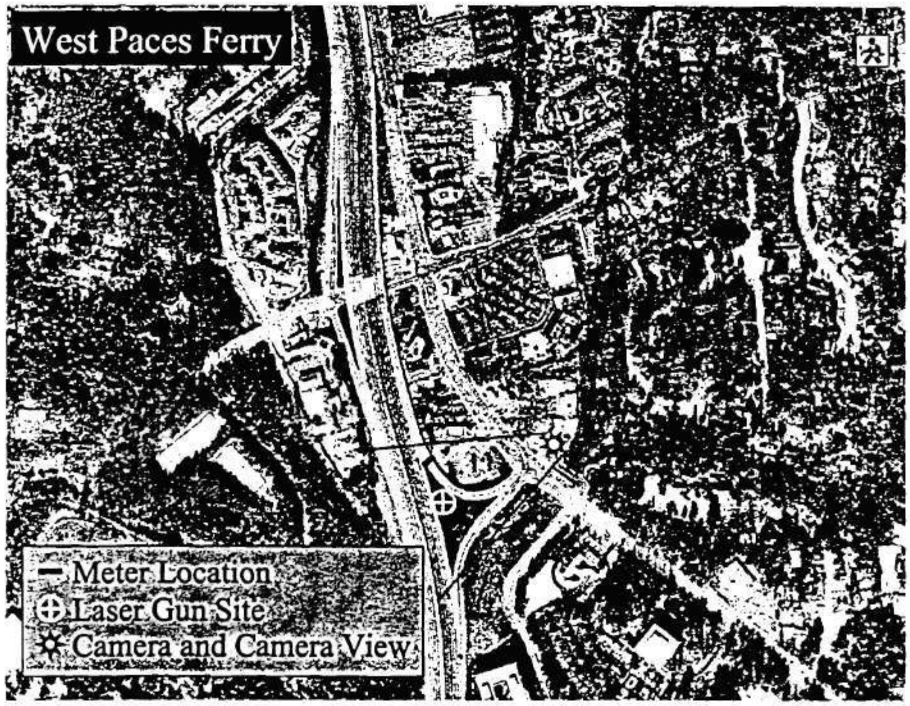


Figure 4-6
Laser Rangefinder Data and Video Data Collection Locations – West Paces Ferry



4.3.2.2 Probe Vehicle Deployment

The probe vehicles instrumented with DMIs were used to supplement the LRF data, or fill in where it was not practical to use the LRFs. The primary use of the probe vehicles was to collect data along the entire study area mainline section. In addition, probe vehicles captured vehicle activity on portions of the onramps where the use of LRFs was not practical, safe, or feasible. For the most part this consisted of curved sections of a ramp where the use of an LRF would be ineffective. The two primary locations were this occurred was on the Northside Drive onramp and the West Paces Ferry Road onramp, from the top of the ramp to the ramp meter stop bar. The probe vehicles were used on the Moores Mill Road onramp as well.

To acquire data with instrumented vehicles, standard data collection procedures were developed. This procedure was used in the collection of all data using the instrumented vehicles. This procedure was adapted from the procedures developed by Sierra Research during cycle development work (Austin, et al. 1993). An outline of the car-following procedures for probe vehicles is shown in Table 4-5 . Complete driver instructions, procedures and sample log sheets can be seen in the data collection manual shown in Appendix C.

During the primary data collection phase in May and June, at least one vehicle was in operation collecting mainline activity data for the entire study area. Probe vehicles were not deployed during the last four data collection sessions. On six of the days, there were two vehicles collecting mainline data. Due to ramp data collection needs and mechanical problems, it was not always possible to run both vehicles on every data collection day. On four occasions, one of the vehicles was collecting ramp activity data at one of the above-discussed locations, while the other collected mainline data.

Table 4-5
Summary of Car Following Instructions

Target Vehicles: The target vehicle is the vehicle that the instrumented vehicle is following in an attempt to capture the speed and acceleration activity of the target vehicle.

Following the Target Vehicle:
1. Enter the freeway at the designated location.
2. Spots the first white vehicle downstream of (in front of) the chase vehicle), regardless of the lane, and enters that lane (when it is safe to do so).
3. Once in the lane, the vehicle immediately in front of the driver is the target vehicle.
4. Follow the target vehicle and mimic its behavior as best as possible, while maintaining a safe distance from the vehicle (headway). The driver brakes, accelerates, maintains cruise speeds, and changes lanes in the same manner as the target vehicle.
5. A target vehicle must be acquired before the beginning flag for the run (usually a designated roadside sign, bridge pier, etc.) is reached. A target vehicle must be tracked through the run until the ending flag is reached.

Following Above the Speed Limit: On some facilities it is common for vehicles to travel above the speed limit. If runs are aborted because the target vehicle goes above the speed limit, the data sample will be biased due to the lack of vehicles in the sample, which travel above the speed limit. For safety purposes, the probe vehicles were not allowed to exceed the design speed of the freeway (approximately 10 mph over the posted speed limit). If this speed was exceeded or a target vehicle was lost for other reasons a new vehicle was chosen.

Changing Target Vehicles: Each selected target is followed as long as reasonably possible. If a target cannot be followed safely through a lane or speed change, a new target is chosen. If a vehicle gets between driver and the target vehicle, the vehicle immediately in front of the driver becomes the (new) target vehicle. If no vehicle is immediately in front of the driver, a new target vehicle will be acquired using the same procedure used to acquire the initial target.
1. When the vehicle departs the study corridor, a new target vehicle will be acquired using the same procedures used to acquire the initial target,
2. If a vehicle comes between the driver and the target vehicle, the vehicle immediately in front of the driver becomes the (new) target vehicle.
3. If a vehicle changes lanes in busy traffic (or some other erratic maneuver) and cannot be followed, the driver will duplicate the maneuver safely as soon as possible. Once the maneuver is complete and the driver is in the new lane, the vehicle immediately in front of the driver becomes the (new) target vehicle.

In total, 20 vehicle days of data were collected on the mainline section over the course of the data collection period. This accounts for 212 complete probe vehicle runs, from the beginning of the study area from the Williams Street onramp to the Mount Paran Road off-ramp. A complete summary of the mainline probe vehicle data runs is shown in Table 4-6.

Table 4-6
Summary of Probe Vehicle Runs for the Mainline Section

Run Data	Number of Runs Vehicle 1, (Dodge)	Number of Runs Vehicle 2, (Ford)	Total
May 3, 1999	11	0	11
May 4, 1999	10	0	10
May 10, 1999	12	13	25
May 11, 1999	9	12	21
May 12, 1999	15	11	26
May 17, 1999	12	11	23
May 19, 1999	10	13	23
May 20, 1999	10	0	10
May 24, 1999	12	9	21
May 25, 1999	11	0	11
May 27, 1999	0	8	8
May 28, 1999	10	0	10
June 2, 1999	2	0	2
June 4, 1999	11	0	11
June 9, 1999	0	0	0
June 10, 1999	0	0	0
July 27, 1999	0	0	0
Total	**135**	**77**	**212**

Eleven vehicle days of data accounting for 276 vehicle runs were performed at the ramp locations, 15 runs at Moores Mill Road onramp, 91 runs at West Paces Ferry Road onramp, and 170 runs at Northside Drive onramp. These data were used to validate and supplement the LRF data. The onramp data collection runs for the probe vehicle are summarized in the following Table 4-7.

Table 4-7
Summary of Probe Vehicle Runs for the Onramp Locations

Run Data and Ramp Location	Number of Runs Vehicle 1, (Dodge)	Number of Runs Vehicle 2, (Ford)	Total Number of Runs
May 13, 1999 Northside Drive	9	0	9
May 25, 1999 West Paces Ferry Road	0	25	25
May 26, 1999 Northside Drive	48	0	48
May 27, 1999 West Paces Ferry Road	29	0	29
May 28, 1999 Northside Drive	0	30	30
June 29, 1999 West Paces Ferry Road	18	0	18
July 6, 1999 Moores Mill Road	14	0	14
July 13, 1999 Northside Drive	21	0	21
July 15, 1999 Northside Drive	23	0	23
July 20, 1999 West Paces Ferry Road	19	0	19
July 27, 1999 Northside Drive	39	0	39
Total	**220**	**55**	**275**

4.3.2.3 Subfleet Characteristics Data

To develop the subfleet characteristic information needed for the MEASURE model, license plate data were collected for a sample of vehicles. Mainline vehicle license plates were sampled by recording plates from the Moores Mill Road overpass using a spotting scope and an audio recorder. Registration data were used to associate plate data with VINs, which were decoded to provide detailed fleet information. Over 5,000 mainline vehicle plates were collected.

Ramp fleet mix data were collected on five days at the Mores Mill Road Ramp concurrent with the collection of the LRF data at that location. These data were used to supplement the data collected by the remote sensing crews deployed at all of the ramps during the data collection period (see Chapter 7). Remote sensing crews collected two to three days of data at each ramp location providing fleet mix data for over 20,000 vehicles operating on the ramps during the data collection period.

The mainline and ramp data were combined to create a single database representative of the fleet operating in the study area during May and June. This database contained critical information for each vehicle, which was used during the emissions modeling process. This included model year, number of cylinders, emissions control type, weight, and odometer reading from the last inspection maintenance check.

4.3.2.4 Traffic Volume Data

Concurrent with the collection of vehicle modal activity data, traffic volume data were also collected. Video cameras and Nu-Metric devices were used to collect the traffic count data. A combination of GDOT traffic management center (TMC) freeway surveillance cameras and portable video cameras were used to record the traffic movements during the data collection periods. The Nu-Metric devices were used on some ramp locations when cameras were not available or convenient to employ.

The video cameras were used to record freeway mainline traffic, onramp and off-ramp volumes, and turning movement traffic at all intersections where the arterial system connected with the study area ramp system (Northside Drive, Howell Mill Road, Moores Mill Road, and West Paces Ferry Road).

Twelve TMC camera views were used to record most of the mainline and onramp and off-ramp activity. Five portable cameras were used to record turning movement activity on and off of the northbound ramps. Over 500 hours of videotape were recorded during the data collection effort. These data were later reduced in the lab and entered into a database to create a comprehensive traffic count dataset for every day that modal activity data were collected. Figures 4-3 to 4-6, presented earlier, also illustrate the mainline freeway and onramp video data collection locations.

4.4 Data Reduction

The data reduction procedures included the processing of all the data collection elements, but the focus was on the preparation of the LRF data for analysis. The data reduction process was comprised of several steps including data cleaning (i.e. removing errant data), data transformation (i.e. post processing data into a useable from), data coding, and data storage. Not all steps were required for all data elements. The reduction of the license plate data, traffic count data, and probe vehicle data, which will be discussed first, only required simple processing and manipulation. The LRF data reduction, presented in the final section, required a more sophisticated reduction process.

4.4.1 License Plate Data Reduction

The license plate data used for the subfleet characterization was collected in two different forms and therefore required two reduction procedures. The mainline data were collected manually through the use of audio recorders. The ramp data were collected through the use of video cameras. Both datasets were reduced to spreadsheet format, which included the location and date/time stamp. The digital data were then matched with the Georgia Department of Revenue vehicle registration database to match vehicle identification numbers (VINs), model year information, and vehicle type information to the plates. A VIN decoding software was then used to append additional vehicle data to the plate data. These data included make, model, number of engine cylinders, fuel transfer type, emissions control, and vehicle weight. The next step was then to match the VIN to the state inspection and maintenance database and append the final data pieces. These include the odometer reading and transmission type.

The final step was then to combine all the data into a single database so that it could be used to provide the fleet technology and age information necessary for the MEASURE model algorithms. Over 30,000 vehicle plates were recorded during the course of this project, but many of the recorded plates did not lead to complete information. This was the result of several factors. First, many plates were recoded or reduced incorrectly resulting in a mismatch with the registration database. In addition, out-of-state plates cannot be matched with the registration database. Secondly, oftentimes-valid VINs will not be decoded nor match the inspection maintenance database. At each step of the process, 10 to 20 percent of the data yield incomplete information. As a result, of the over 30,000 plates collected, complete information was only acquired for approximately 6,000 vehicles. An overall 20 percent match rate may seem low, but the 6,000 complete records and additional partial records provided sufficient data for the MEASURE model.

4.4.2 Traffic Count Data Reduction

Traffic count data used to assess traffic operations conditions and provide traffic volumes and flow rates were collected using video surveillance. The field videos were viewed and reduced in the lab using TDIP traffic count software. The data reduction process included coding the counts for date, time, vehicle classification, and lane assignment for the mainline vehicles. Once these data were recorded into digital format, they were combined into a single database. These data were then binned in five-minute groups by location, and processed to estimate traffic volumes at location where data were not collected. This provided for a complete traffic count dataset, which was then used to match with the probe vehicle and LRF data for analysis.

4.4.3 Laser Rangefinder Data Reduction

Due to the high-frequency data capture and sheer volume of data, the LRF dataset provided the largest data reduction challenge. As discussed earlier, the LRFs were operated in real-time range mode in order to collect the most accurate and detailed data. Because the LRF data were collected in this mode, extensive post processing was required. When operating in real time range mode, the output from the LRF unit consists of simple distance measurements. The information needed to produce speed/acceleration profiles must be calculated from this field data. The consistency of the LRFs makes this a reasonably easy process for a single trace, but it is complicated when large amounts of data are considered. The LRFs receive precisely 238 readings a second; therefore the time between each distance measurement is always the same. Knowing this, the distance and time information were used to calculate speed and the rate of change in speed (i.e. acceleration).

In the field, each vehicle trace was recorded as a single data file that was stored on a PCMCIA data card inserted into the LRF unit, which was periodically downloaded to a laptop computer for temporary storage. At the end of each data collection day, all of the LRF files along with their accompanying JAMAR vehicle classification files were downloaded and stored in the lab under unique folders indicating the date and location for which the files were associated. On a given day there were hundreds of LRF files from each data collection site, but only one JAMAR file from each site. The single JAMAR file contained the vehicle classification information for all traces from that site. An example of a raw LRF data file is shown in Table 4-8 and an accompanying JAMAR vehicle classification file can be seen in Table 4-9.

Table 4-8
Sample LRF Output File

00223.1f
00223.3f
00223.3f
00223.3f
00224.1f
00223.3f
00224.1f
00224.1f
00224.1f

Table 4-9
Sample JAMAR Vehicle Classification Output File

Jamar Board Count{	#1
Site Code:	00220520
Collection Date:	05-20-99
Start Time:	15:31:0.00
6 axle, multi-unit	15:31:00.81
2 axle, 6 tire single unit	15:32:43.17
Car	15:33:30.45
Car	15:33:50.26
3 axle, single unit	15:34:31.28
Car	15:35:11.37
Car	15:35:42.68
Pickup/Van/Motor Home	15:36:11.45
Pickup/Van/Motor Home	15:36:33.84
Pickup/Van/Motor Home	15:37:06.12
Car	15:37:42.79
Car	15:38:12.82

The LRF data reduction process was divided into four distinct steps. The first was to reconcile the LRF output with the JAMAR vehicle classification file. The second was to process the LRF distance readings into second-by-second vehicle speeds and acceleration rates. The third step was to condense the individual data files into a single database. The fourth step was to group the data into 15-minute bins for analysis. The completion of these four step resulted in a single convenient dataset that could be used for all the analysis required for this research.

The PCMCIA cards used to store the real-time LRF data can store up to 100 data files, or vehicle traces. The 2Mb data card typically ran out of memory before 100 traces could be recorded and only 50 to 60 traces typically fit on a single card. In the field, when a card was filled it was replaced by a new card and sampling continued. A field supervisor moved from location to location and downloaded completed cards to the local laptop computer, making the cards available again for data collection.

Each LRF file must be matched with a JAMAR file so that the vehicle classification of the trace would be known. A single JAMAR file has to be created for each PCMCIA card containing LRF data. At the end of a given day, there was only one JAMAR file for all of the LRF data from a particular site. Therefore, as part of the data processing, the JAMAR file needed to be divided into parts to match the appropriate number of LRF file groups. It was also necessary for each new JAMAR file to contain the same number of vehicles as there were files in the group with which it was matched. For example, if a data collector recorded 10 vehicle traces on a particular PCMCIA card, then its matching JAMAR file needed to contain 10 vehicle classification records. The LRF log sheets were used to reconcile discrepancies between the LRF data and the JAMAR data. On some occasions, data were lost if an accompanying JAMAR file did not exist or could not be reconciled. Such instances resulted in a loss of approximately 10-15 percent of the LRF traces.

Once the data were matched with a JAMAR file, the second data processing step was performed. A FORTRAN program (RANGE72) was developed for processing the raw LRF data into usable speed and acceleration information for each trace. At the same time, this program extracted the vehicle classification, date, time, and metering condition (i.e. meter on or meter off) data from the JAMAR file and append it to the processed LRF data. The program also filtered out errant or inaccurate LRF data points resulting from data collector or LRF error. The conclusion of this step ended with usable data, in a flat file form as shown in Table 4-10. The output of the RANGE72 program assigned each vehicle trace a single record which included a trace number, location code, date, time, metering code, vehicle classification code, trace increment (second), distance, speed (mph), and acceleration rate (mph/sec). The last four data fields (increment, distance, speed, and acceleration rate) were repeated for every second (increment) of the trace.

Table 4-10
Example of Laser Rangefinder Data File
After Processing in the RANGE72 Program

1,	00220520,	05-20-99,	17:36:04,	on,	2,	1.00,	71.7,	20.5,	5.4,
2,	00220520,	05-20-99,	17:36:40,	on,	3,	1.00,	37.9,	16.4,	5.8,
3,	00220520,	05-20-99,	17:37:08,	on,	3,	1.00,	94.9,	25.2,	5.0,
4,	00220520,	05-20-99,	17:37:44,	on,	2,	1.00,	72.5,	20.3,	3.2,
5,	00220520,	05-20-99,	17:38:19,	on,	3,	1.00,	22.9,	11.8,	4.5,
6,	00220520,	05-20-99,	17:38:48,	on,	3,	1.00,	12.2,	9.6,	5.6,

The third data processing step condensed the flat data files into a single database, while also transposing the data format. To store the data more efficiently, the new database structure stratified the data into two tables: one containing just the trace information and the other containing the vehicle and location information. At this time, additional descriptive data (e.g. ramp grade, metering rate, lane number, etc.) was added to another related table in the database. During this process, a final data cleaning procedure was also performed. This included the removal of errant speed and acceleration data not filtered out by the RANGE72 program. Any remaining unrealistic speed or acceleration observations were removed from the dataset.

The fourth and final step was to group the data into bins by date, time (15-min periods), and location. This was a necessary step in order to have the data in a final usable from for analysis. That is, the LRF data had to be normalized before it could be read for analysis. The binning process included normalizing the dataset. During the data collection process the data samples varied by location (i.e. data collection site) and within locations (i.e. at different points along the ramp). Not all vehicles were traced for the same distance along the ramp, which resulted in varying frequency of data points at various points down the ramp. If the data were not normalized by the sample size, the data would be biased and more heavily weighted toward the areas in which the teams collected larger amounts of data. Because it is likely that modal vehicle activity will be different at different points along the ramp section (e.g. at the stop bar versus at the merge area), this was an important process. As a result, the final data analysis consisted of assessing modal activity of vehicles in the aggregate by 15-minutes periods and not as individual vehicle traces. The binned LRF data were appended to the traffic count data to form a comprehensive database that included ramp and mainline traffic flow information.

The four steps discussed above summarize the process used to reduce the raw LRF data into a usable form. The final process related to the LRF data was to assess any biases that potentially exist within the dataset.

4.4.3.1 Assessing Potential Laser Rangefinder Data Bias

Even under ideal conditions it is difficult collect a perfect dataset. The most effective way to handle any limitations with a dataset is to understand any limitations and account for them appropriately. There are two main areas with this particular dataset where biases might exist.

The primary concern was if the data were representative. That is, whether the data represent a random sample of vehicle activity that is representative of the traffic as a whole. Secondary to this is whether or not the sample was constant across day and location and particularly within each location (e.g. across the complete ramp section).

To test for any potential bias in the sampling procedure, the LRF data sample was compared to the observed vehicle count data. The vehicle classification of the LRF sample was compared to the vehicle classification distribution of the total traffic volume. As can be seen in Table 4-11, the control traffic mix distribution closely matched the sampled traffic distribution for the LRF data. This was particularly true for automobiles and SUVs, the vehicles of concern for this research. This analysis indicated that the dataset was free of any systematic sampling bias. Therefore the researchers assume that any sampling-related errors in the data (e.g. as a function of driver behavior) would also be randomly distributed.

Table 4-11
Comparison of Laser Rangefinder Sample with Observed Traffic

LOCATION	LRF Sample			Observed Traffic		
	% Cars	% SUVs	% Trucks	% Cars	% SUVs	% Trucks
Northside Drive Ramp	65.3	33.6	1.1	67.8	31.5	0.7
Howell Mill Road Ramp	59.6	36.4	4.0	63.0	34.1	2.9
Moores Mill Road Ramp	52.3	44.9	2.8	54.0	43.9	1.7
West Paces Ferry Road Ramp	61.1	36.9	2.0	61.5	36.6	1.9
Mainline	65.9	30.9	3.2	64.0	34.0	2.0

Due to the characteristics of the LRFs and the application for this research, there was concern that larger vehicles would be traced for longer distances resulting in a bias toward larger vehicles in the dataset at longer ranges. The primary concern was that larger SUVs might bias the data by being over-represented in certain parts of the dataset. Since SUVs are likely to be operated (i.e. accelerate) differently than typical passenger vehicles, this would not be desirable. Ideally, data with a uniform distribution of vehicles by type by distance from the data collector would be the goal. Therefore, the distribution of SUVs by distance from the LRF collection site was tested to see if it was uniform. The Chi-Squared Goodness-of-fit test was used to evaluate the distribution for each data collection site (Knaji, 1999). For each case, as shown in Table 4-12, the test showed that since the Chi-Squared value (for 16 degrees of freedom) was not exceeded for any case, the distribution over distance was uniform, with a high (i.e. 99.5%) level of confidence.

Table 4-12
Chi Squared Goodness of Fit Test Results
Sport Utility Vehicle Sample Distribution

LOCATION	Chi Squared Value	Chi Squared Critical (16df)(.005)	Null Hypothesis Accepted
Northside Drive Ramp	21.72	34.27	Yes
Howell Mill Road Ramp	6.02	34.27	Yes
Moores Mill Road Ramp	7.06	34.27	Yes
West Paces Ferry Road Ramp	16.12	34.27	Yes

An over-representation of larger vehicles did not exist within the LRF data.

4.4.4 Probe Vehicle Data Reduction

Each probe vehicle run, whether it was on the mainline section or a ramp, was saved by the data collector as an individual file on a laptop computer. At the end of each data collection day, the files on the laptop were downloaded and stored in the lab. The output from the DMI was in second-by-second speed and distance format, and therefore did not require as much post processing as with the LRF data. A sample of the DMI data output is shown in Table 4-13. At the end of the data collection period, all the data files were condensed and aggregated into a single summary data file. The probe vehicle data were analyzed separately for each location and stratified by ramp metering condition. The data were used for small-scale analysis (i.e. 15-minute bins) in the same way that the LRF data were used. For the ramp locations, these data provided speed/acceleration information for locations where the LRF used was not practical. For the mainline section, this provided trace data for entire freeway section and was stratified by type of section (i.e. merge, diverge, weave, and basic).

Table 4-13
Sample Distance Measurement Instrument (DMI) Data Output File

Count,	Distance,	Change in Distance,	Speed,	Time
1.	0	0	0	15:47:09
2.	0	0	0	15:47:10
3.	0	0	0	15:47:11
4.	10	10	20	15:47:12
5.	34	24	17	15:47:13
6.	56	22	16	15:47:14
7.	80	24	17	15:47:15

Once all of the data were collected and reduced to a usable format, the analytical procedures discussed in Chapter 3 were implemented. Chapter 5 contains the analytical results.

CHAPTER 5
PRESENTATION OF FIELD FINDINGS

One of the objectives of this research was to develop a method to sample representative modal activity on freeway onramps and mainline sections of the Atlanta ramp metering system. This methodology was presented in Chapters 3 and 4. The main objectives of this research were to assess the emissions impacts of ramp metering systems and determine the design and traffic conditions that influence modal activity and emissions rates. This Chapter presents the analyses findings related to these objectives. The Chapter first presents the observed differences in modal activity under metered and non-metered conditions. A discussion of the emissions estimates produced using both the MEASURE Aggregate Modal Model and MOBILE5b model follows. The final section will include the findings related to differences in observed modal activity under various design and traffic demand conditions.

5.1 Modal Activity Findings

Ramp meters that require vehicles on ramps to come to a complete stop on a freeway will clearly influence modal activity. If nothing else, metering will decrease the average speed of entering vehicles, resulting in longer periods of operation for each vehicle traversing the onramp. The question is to what degree are modal activity and emissions increased and what are the offsetting factors resulting from improvements to mainline traffic flow. Table 5-1 shows the difference in modal activity for all ramps combined and the mainline section based on three measures.

Table 5-1

Average System Wide Modal Activity for Metered and Non-Metered Conditions*

Modal Activity Measure	Ramps Metered	Ramp Non-Metered	Mainline Metered	Mainline Non-Metered
Average Speed (mph)	32	41	63	62
Average Acceleration (mph/sec)	2.2	1.8	0.14	0.12

* From a Combination of Laser Rangefinder and Probe Vehicle Data

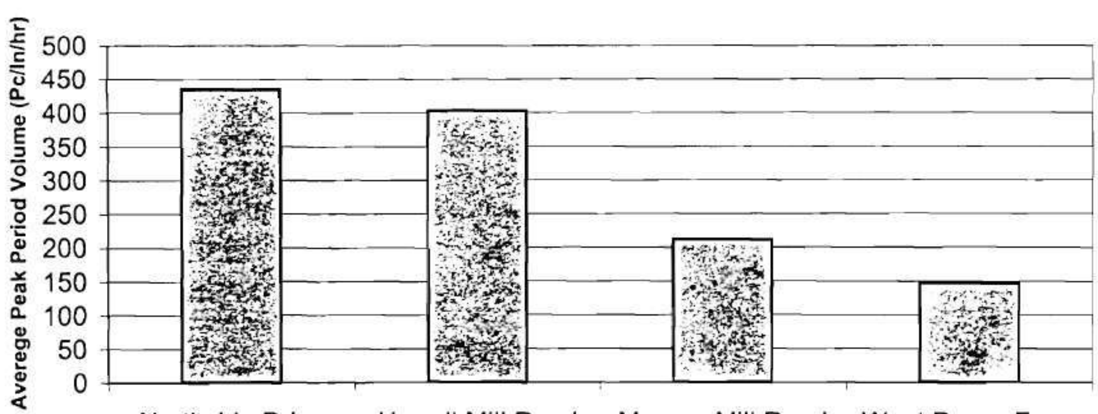
As would be expected, the average speeds are lower and the acceleration rates are higher on the onramps under metered conditions. More detailed modal activity findings for each individual location are discussed in the following sections.

5.1.1 Onramp Modal Activity

The LRF data, supplemented by the probe vehicle data, show significant differences in the level of modal activity on the study area onramps, as a function of the metering condition. Several different emissions-related speed and acceleration measures are presented to illustrate the magnitude of differences in observed modal activity. These include: average speed, average acceleration rate, percent of cycle with acceleration greater than 3 mph/sec, percent of cycle with acceleration greater than 6 mph/sec, percent of cycle with deceleration greater than 2 mph/sec, percent of cycle with inertial power surrogate (IPS) greater than 90 mph^2/sec, and percent of cycle with IPS greater than 120 mph^2/sec. There are significant modal activity differences between vehicles approaching the ramp meter stop bar and those accelerating away from the ramp meter stop bar to the merge area. The data for each ramp location are presented separately for the deceleration zone (before the stop bar) and the acceleration zone (after the stop bar). The modal activity data for each location are also presented in graphical form as a joint acceleration-speed probability density function (JASPROD). The JASPROD, known as a Watson plot, summarizes the relative frequency of different combinations of speeds and accelerations and displays it in a three-dimensional format.

The modal activity findings are presented for each onramp are presented in the following separate report sections: Northside Drive, Howell Mill Road, Moores Mill Road, and West Paces Ferry Road. The Northside Drive and Howell Mill Road locations experienced the heaviest traffic volumes each carrying the equivalent of over 400 passenger cars an hour, as can be seen in Figure 5-1. The Moore Mill Road and West Paces Ferry Road locations experience much lighter traffic carrying the equivalent of 150 to 200 passenger cars over an hourly average.

Figure 5-1
Average Hourly Traffic Volumes by Ramp Location (Passenger Car Equivalent)



5.1.1.1 Northside Drive Onramp Modal Activity

Table 5-2 indicates an increase in modal activity under metered conditions that will likely lead to increased occurrence of enrichment and vehicle emissions. These modal variables are important inputs to the MEASURE Aggregate Modal Model. The exception to this is for the activity associated with the deceleration zone. Reductions in average vehicle speeds also increase the amount of time that a vehicle spends within the ramp area. Hence, even with a constant gram/second emissions rate, vehicle emissions in the onramp zone will increase with a reduction in average speed, due solely to the additional time spent in ramp operations. Even though the model variables are lower in the deceleration zone under metered conditions, the increased engine time associated with the lower travel speed will likely result in an increase in mass emissions. The emissions rate for metered vehicle may be lower on a grams per second basis, but the vehicle will occupy the onramp for a longer period resulting in higher net emissions. The only modal variable that is not lower under metered conditions in the deceleration zone is the percent of cycle with deceleration greater than 2 mph/second. This would be expected, and is consistent across all sites since vehicles are required to come to a stop at the ramp meter location.

Table 5-2
Summary of Modal Activity for the Northside Drive Onramp

Modal Activity Variable	Northside Drive Onramp			
	Metered		Non-Metered	
	Deceleration Zone	Acceleration Zone	Deceleration Zone	Acceleration Zone
Average Speed (mph)	12	39	23	40
Average Acceleration (mph/sec)	-0.3	3.1	0.4	2.8
Percent of Cycle Acceleration > 3 (mph/sec)	2.2	26	1.9	11
Percent of Cycle with Acceleration > 6 (mph/sec)	0.3	1.0	0.2	0.1
Percent of Cycle with Deceleration > 2 (mph/sec)	9.3	2.2	1.7	1.8
Percent of Cycle with IPS > 90 (mph^2/sec)	1.4	30	2.2	21
Percent of Cycle with IPS > 120 (mph^2/sec)	0.5	10.5	1.0	6.8

By comparing the surface of Watson plots (or JASPRODs), differences in model activity for emissions critical regions are highlighted. JASPRODs for the non-metered and metered conditions on the deceleration zone for the Northside Drive onramp are shown in Figures 5-2 and 5-3. These figures clearly illustrate the difference in modal activity for these conditions. When the meter is operating, modal activity is more dispersed and weighted toward negative acceleration (i.e. deceleration). When the meter is not operating, the distributions are more uniform, with much less activity in the deceleration area. Figures 5-4 and 5-5 show the modal activity for the Northside Drive acceleration zone. Again, the non-metered distribution is more uniform, but the modal activity shift for the metered condition is to the high acceleration area rather than the deceleration area.

Figure 5-2
Northside Drive Onramp Deceleration Zone under Non-Metered Condition
Joint Acceleration-Speed Probability Density Function (JASPROD)

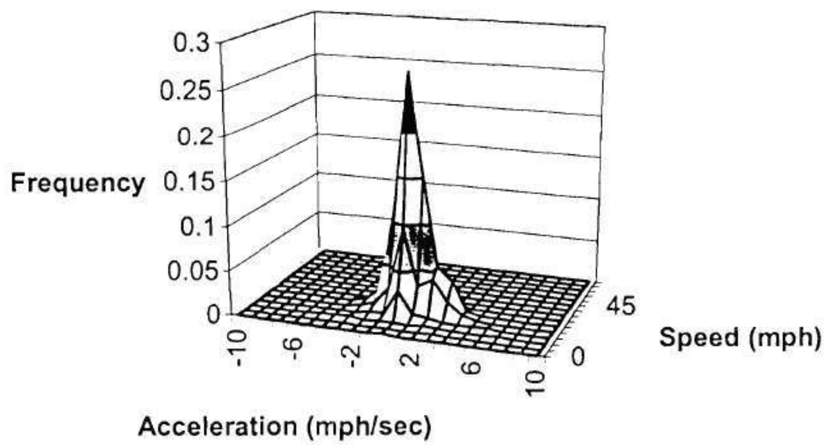


Figure 5-3
Northside Drive Onramp Deceleration Zone under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

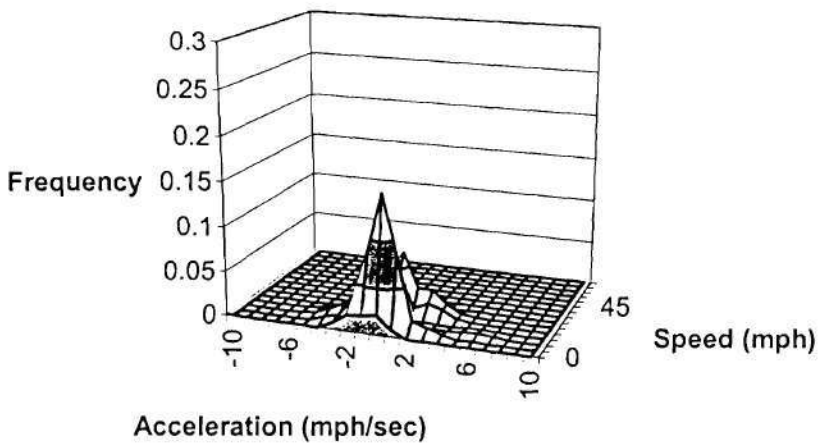


Figure 5-4
Northside Drive Onramp Acceleration Zone under Non-Metered Condition
Joint Acceleration-Speed Probability Density Function (JASPROD)

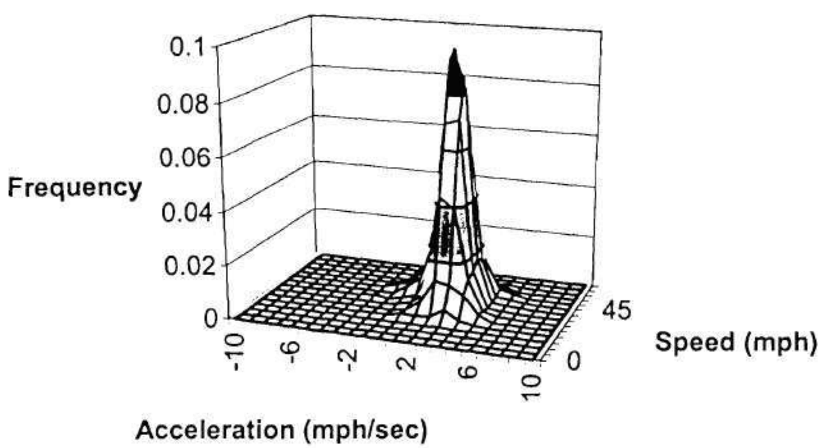
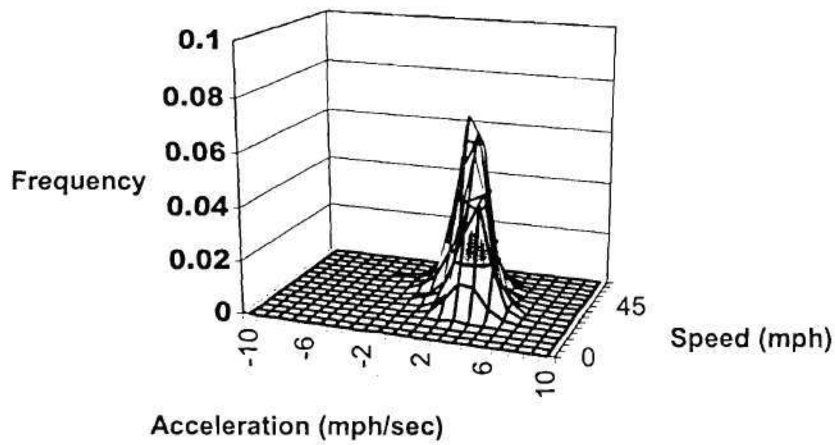
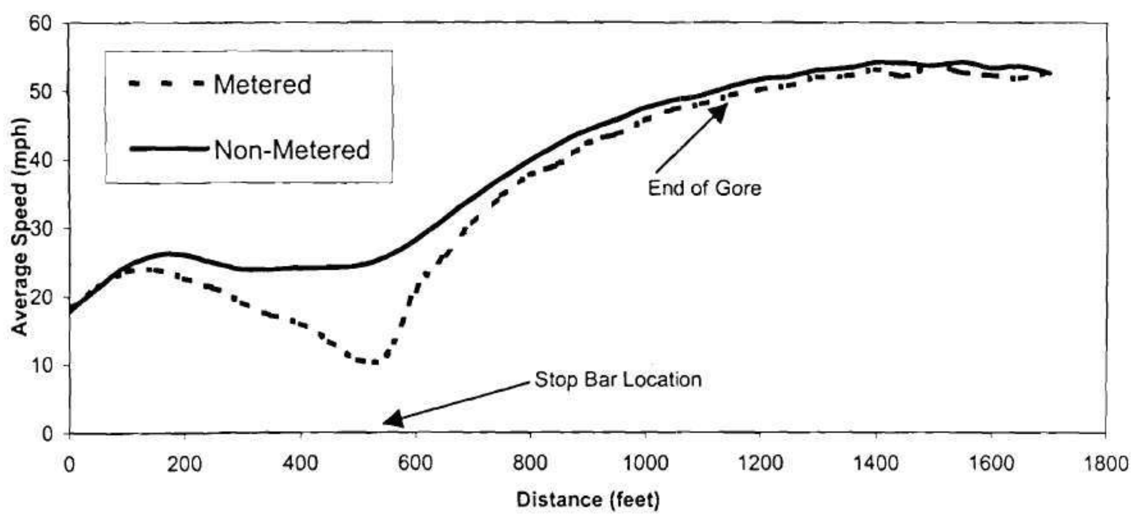


Figure 5-5
Northside Drive Onramp Acceleration Zone under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



The modal variables in Table 5-2 included the average vehicle operating speed on the two ramp zones under metered and non-metered conditions. The average speed trace under each condition as shown in Figure 5-6 provides a more informative picture of the average vehicle speed at different points along the onramp section.

Figure 5-6
Average Vehicle Speed Profile for Northside Drive Onramp



The vehicle speed profiles above are illustrated in relation to the stop bar and end of gore locations. Because all vehicles are required to come to a stop at the ramp meter stop bar location it would be expected that the speed at this point would be close to zero. The average speed at the stop bar under metered conditions is approximately 10 mph. There are several explanations for the observed speed at the stop bar being higher than expected. The average speed data points for the above trace is an average over a 50 foot distance bin centered on the stop bar, therefore the actual spot speed precisely at the stop bar location is less the 10 mph. This notwithstanding, even if the speed trace was derived using a smaller distance increment (e.g. one foot) the observed speed at the stop bar would not likely be zero. This due to the fact that many vehicles "creep" through the stop bar area anticipating a green signal and then proceed down the ramp without coming to a complete stop. An even smaller number of vehicles disobey the signal completely and cross the stop bar at speeds similar to those observed when the ramp meter is not operating. These factors result in average speeds at the stop bar greater than zero, but ramp meter violations do not appear to be a significant problem in and of themselves. The observed violation rate for the Northside Drive onramp during the course of this research was one percent. As can be seen in Table 5-3, apart from the Moores Mill location the violation rate was considerably low. The lowest violation rate was observed on the Howell Mill Road onramp, the modal activity for this ramp is discussed in the next section.

Table 5-3
Ramp Meter Violation Rate

Location	Northside Drive Onramp	Howell Mill Road Onramp	Moores Mill Road Onramp	West Paces Ferry Onramp
Violation Rate (%)	1.0	0.7	5.8	1.6

5.1.1.2 Howell Mill Road Onramp Modal Activity

The Howell Mill Road onramp modal activity revealed more modal extremes than the activity on the Northside Drive onramp. As with the Northside location, most all indictors suggest measurable increases in modal activity in the acceleration zone under metered operation, deceleration rates notwithstanding. As can be seen in Table 5-4, the modal activity variables in the deceleration zone are lower under metered conditions. Engine load and acceleration rates decline as vehicles approach the stop bar, but, as explained earlier, this will not necessarily lead to a reduction in over all emissions due to change in the average speed. The net change in emissions also needs to be assessed in conjunction with the drastic increase in engine load in the acceleration zone, as measured by the large changes in percent of cycle with IPS greater than 90 and IPS greater than 120.

Table 5-4
Summary of Modal Activity for the Howell Mill Road Onramp

Modal Activity Variable	**Howell Mill Road Onramp**			
	Metered		**Non-Metered**	
	Deceleration Zone	**Acceleration Zone**	**Deceleration Zone**	**Acceleration Zone**
Average Speed (mph)	22	36	35	49
Average Acceleration (mph/sec)	-0.2	3.2	1.9	1.6
Percent of Cycle Acceleration > 3 (mph/sec)	6	29	9	2.2
Percent of Cycle with Acceleration > 6 (mph/sec)	0.9	2.4	0.1	0.01
Percent of Cycle with Deceleration > 2 (mph/sec)	52	2	9	5
Percent of Cycle with IPS > 90 (mph^2/sec)	3.5	26	11.0	6.0
Percent of Cycle with IPS > 120 (mph^2/sec)	1.6	10	3.8	2.1

Figures 5-7 to 5-10 show the variations in modal activity graphically for this location, in the form of Watson Plot JASPRODs.

Figure 5-7
Howell Mill Road Onramp Deceleration Zone under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

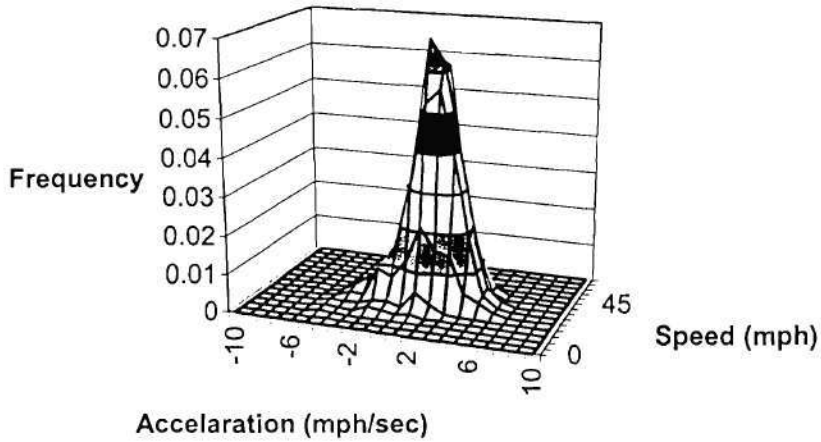


Figure 5-8
Howell Mill Road Onramp Deceleration Zone under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

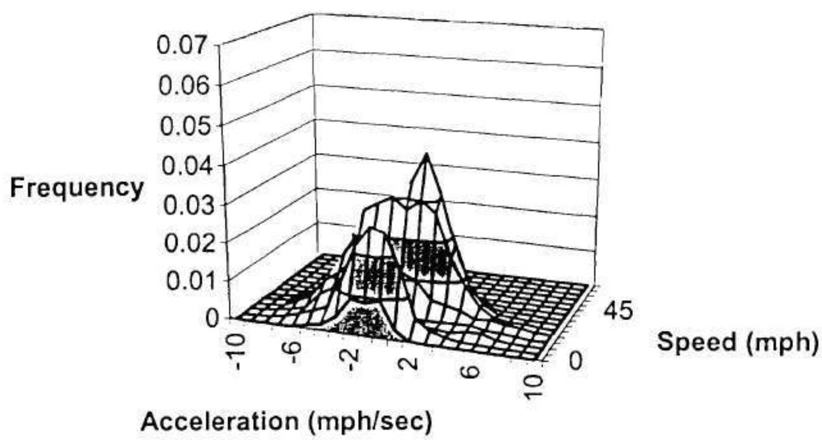


Figure 5-9
Howell Mill Road Onramp Deceleration Zone under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

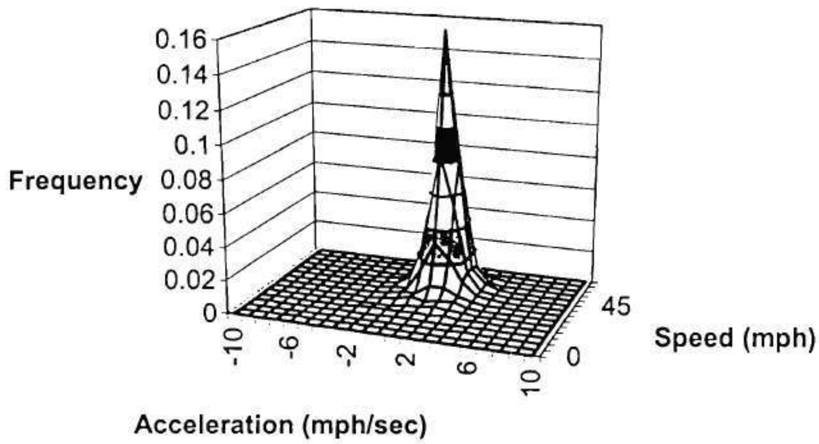
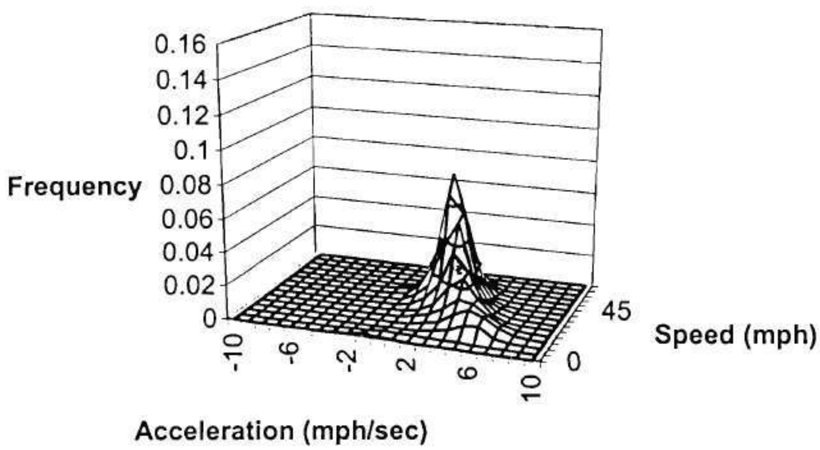
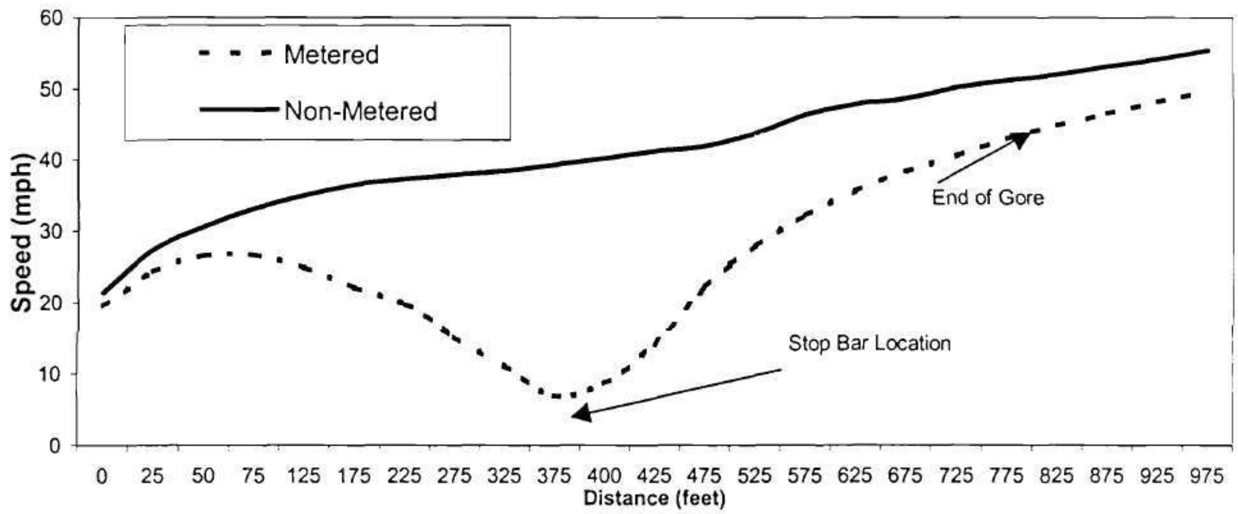


Figure 5-10
Howell Mill Road Onramp Acceleration Zone under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



The JASPROD plots for the deceleration zone show the dispersed and heavy deceleration activity under the metered condition. The shift in activity in the deceleration zone for this location is even more extreme then at other sites due to the steep (-7%) grade at the approach to the ramp meter stop bar. The distribution in the acceleration zone is consistent for the two locations, but the shift to higher acceleration activity under metered conditions is evident. The average speed traces shown in Figure 5-11 depict the typical vehicle trajectory down the Howell Mill Road onramp under metered and non-metered conditions.

Figure 5-11
Howell Mill Road Drive Onramp Average Vehicle Speed Profile



5.1.1.3 Moores Mill Road Onramp Modal Activity

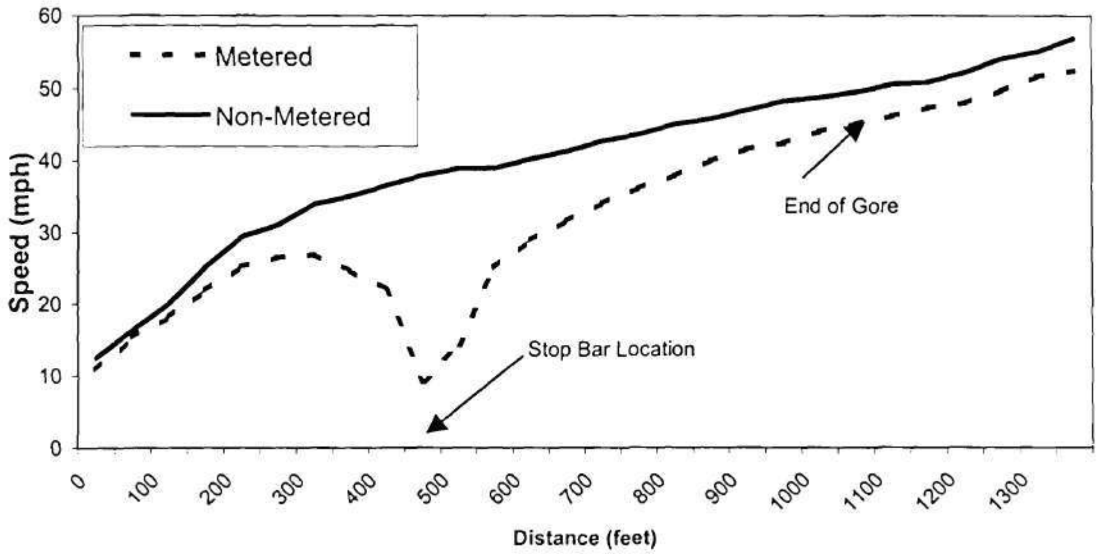
The modal activity trends on the Moores Mill onramp were consistent with that observed at the Northside Drive and Howell Mill Location. Table 5-5 indicates that modal activity increased in the acceleration zone for all measures under ramp metering. Modal activity in the deceleration zone decreased along with a sharp (30%) drop in average speed.

Table 5-5
Summary of Modal Activity for the Moores Mill Road Onramp

Modal Activity Variable	Moores Mill Road Onramp			
	Metered		Non-Metered	
	Deceleration Zone	Acceleration Zone	Deceleration Zone	Acceleration Zone
Average Speed (mph)	19	34	27	45
Average Acceleration (mph/sec)	-0.4	2.6	2.2	1.4
Percent of Cycle Acceleration > 3 (mph/sec)	6.7	16	12.9	3
Percent of Cycle with Acceleration > 6 (mph/sec)	0.3	2.6	0.0	0.2
Percent of Cycle with Deceleration > 2 (mph/sec)	19	5	0.0	8
Percent of Cycle with IPS > 90 (mph^2/sec)	3.8	10.5	39.5	5.9
Percent of Cycle with IPS > 120 (mph^2/sec)	1.6	5.1	24	3.0

The average speed traces for this site can be seen in Figure 5-12. The vehicles operating under metered conditions not only have a slower average speed, but do not appear to fully recover from coming to a stop and enter the merge area at a lower average speed than under non-metered conditions.

Figure 5-12
Average Vehicle Speed Profile for Moores Mill Road Drive Onramp



The graphical representation of the modal activity for this site also consistent with what has been observed at the other locations. As shown in Figure 5-13 and Figure 5-14, the deceleration zone shows extensive deceleration activity under metered conditions and more consistent activity under non-metered conditions. The coarseness of the JASPRODs for the acceleration zone at this site is due to the small data set and not necessarily due to more inconsistent modal activity.

The modal activity in the acceleration zone for the non-metered case reveals very uniform activity as shown in Figure 5-15. The modal activity in the acceleration zone under metered conditions is characterized by a wider range of activity, and more activity in the "emissions critical" high acceleration area. Similar to the pattern observed at the Howell Mill Road location, there is a significant increase in low speed hard accelerations, as seen in Figure 5-16.

Figure 5-13
Moores Mill Road Onramp Deceleration Zone under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

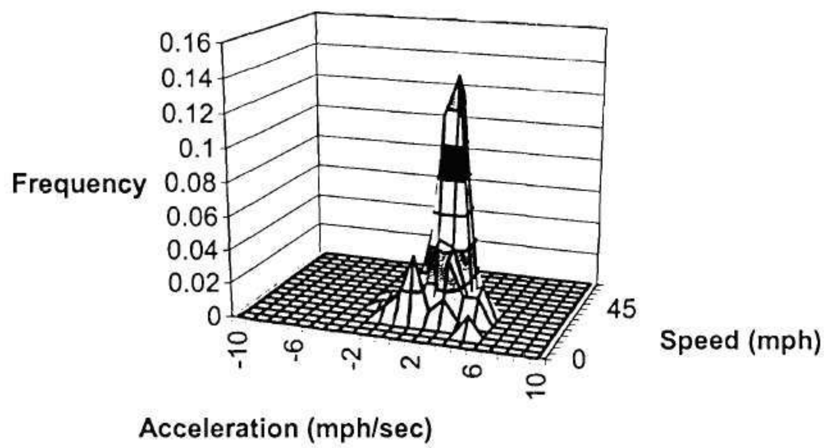


Figure 5-14
Moores Mill Road Onramp Deceleration Zone Under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

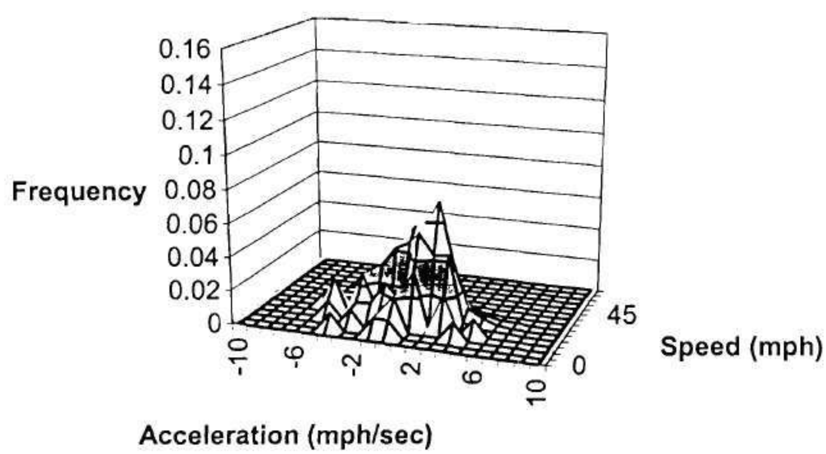


Figure 5-15
Moores Mill Road Onramp Acceleration Zone under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

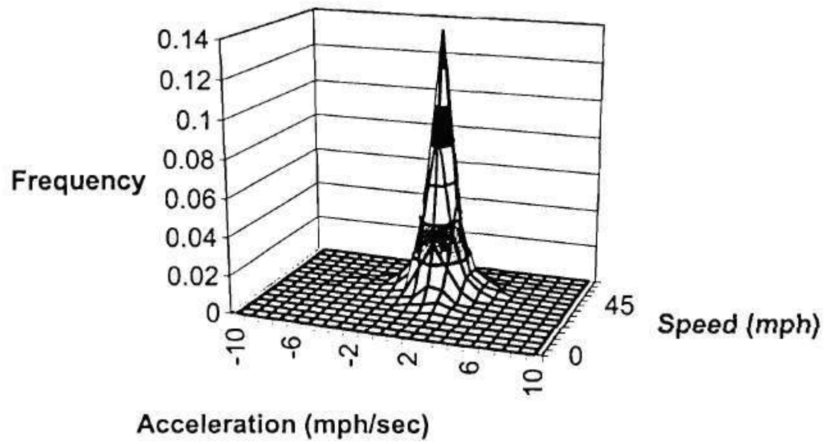
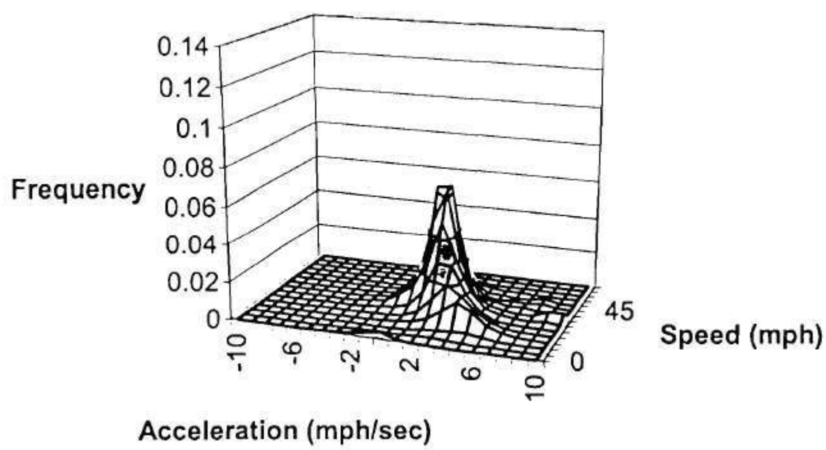


Figure 5-16
Moores Mill Road Onramp Acceleration Zone Under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



5.1.1.4 West Paces Ferry Road Onramp Modal Activity

The modal activity observed at the West Paces Ferry Road site was consistent with the other three onramp locations, but the changes were less severe, as can be seen in Table 5-6. The activity in the deceleration zone under both metering and non-metering conditions was characterized with noticeable levels of deceleration. This is most likely due to the curved approach design of the ramp requiring braking even if the ramp meter is not operating. The activity in the acceleration zone under metered conditions indicated an increase in modal activity, but to a lesser degree than observed at the other locations. That is, the metering has a less significant impact on operating modes because vehicles are already decelerating even when meters are off due to the curved approach.

Table 5-6
Summary of Modal Activity for the West Paces Ferry Road Onramp

Modal Activity Variable	**West Paces Ferry Road Onramp**			
	Metered		**Non-Metered**	
	Deceleration Zone	**Acceleration Zone**	**Deceleration Zone**	**Acceleration Zone**
Average Speed (mph)	16	37	25	44
Average Acceleration (mph/sec)	-0.2	1.9	1.2	1.4
Percent of Cycle Acceleration > 3 (mph/sec)	5.6	9	7.1	4
Percent of Cycle with Acceleration > 6 (mph/sec)	0.0	0.7	0.1	0.2
Percent of Cycle with Deceleration > 2 (mph/sec)	16	11	3.4	10
Percent of Cycle with IPS > 90 (mph^2/sec)	3.2	9.2	10.2	7.8
Percent of Cycle with IPS > 120 (mph^2/sec)	0.6	4.3	5.3	3.5

Watson plots of speed and acceleration for this location are provided in Figures 5-17 through 5-20. As can be seen in these graphs, both the metered and non-metered conditions experienced high levels of both acceleration and deceleration activity.

Figure 5-17
West Paces Ferry Road Onramp Deceleration Zone under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

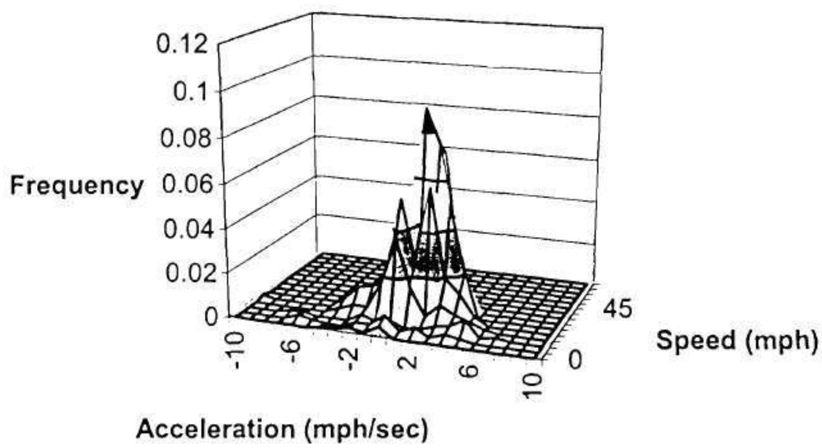


Figure 5-18
West Paces Ferry Road Onramp Deceleration Zone under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

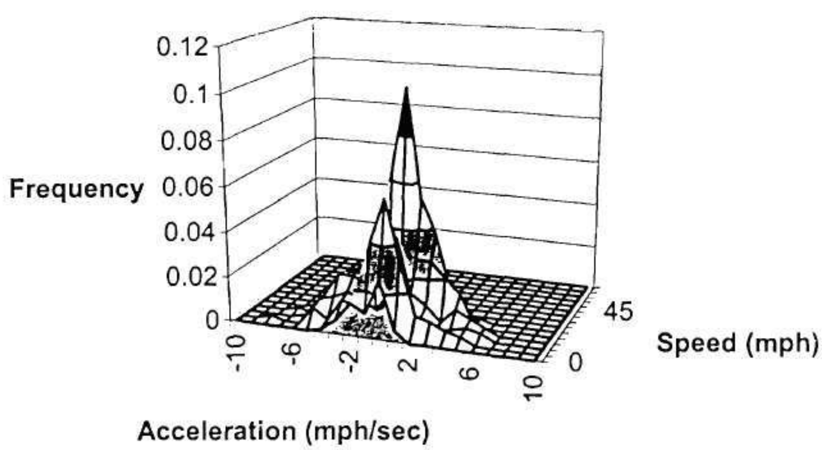


Figure 5-19
West Paces Ferry Road Onramp Acceleration Zone under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

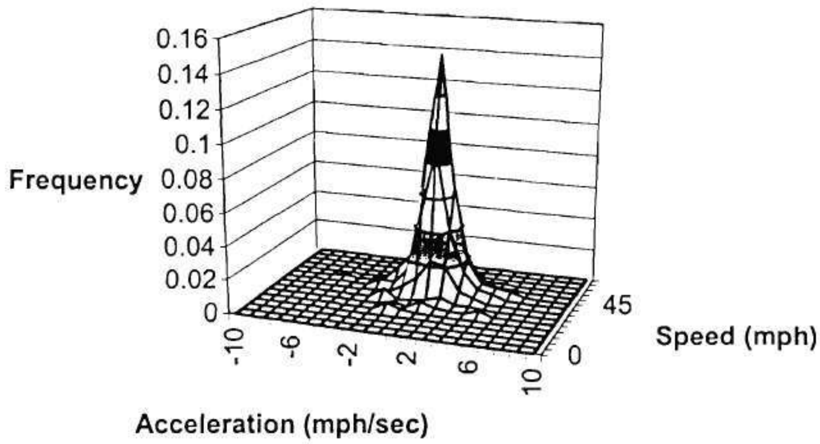
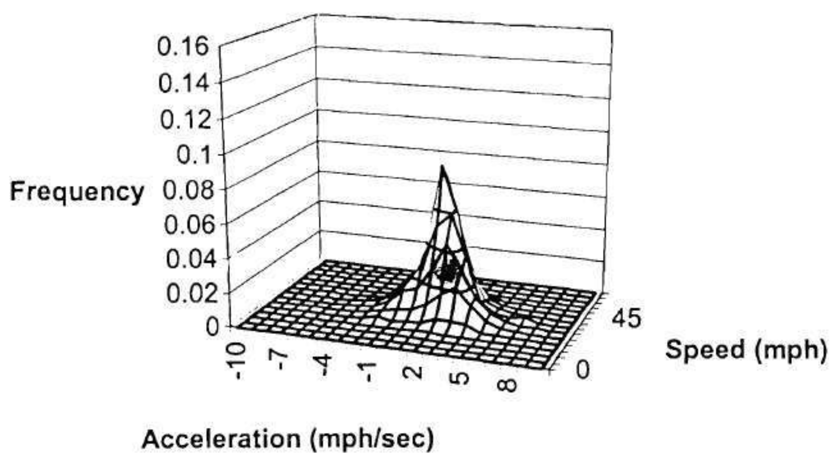
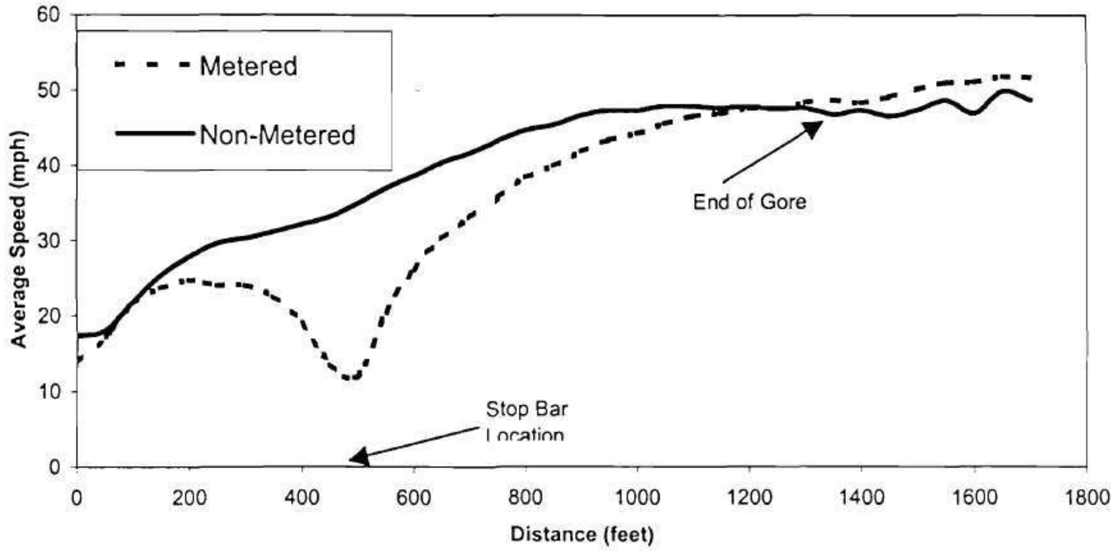


Figure 5-20
West Paces Ferry Road Onramp Acceleration Zone under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



The average sped trace for the West Paces Ferry onramp is shown in Figure 5-21. This figure shows the average vehicle trajectory on the ramp under metered and non-metered conditions.

Figure 5-21
West Paces Ferry Road Drive Onramp Average Vehicle Speed Profile



The researchers anticipated that a measurable increase in modal activity under metered conditions would occur, simply due to the nature of ramp metering. Therefore the above findings are not surprising, but they do provide quantitative assessment of the impact of ramp metering on onramp activity. One of the key questions of this research is how this change in onramp activity relates to changes on the associated mainline sections and the net air quality impacts that result. The mainline modal activity is discussed in the next section, and the latter question is addressed in section 5.2.

5.1.2 Mainline Freeway Modal Activity

The assessment of the freeway mainline activity was performed using the LRF data, while also relying heavily on information from the probe vehicles. The approach was to examine modal activity and the emissions across freeway section functional characteristics. For this analysis, the 4.4-mile mainline section was divided based on three functional criteria that would separate different areas of freeway modal activity. Functional classifications included: basic freeway sections, where vehicles operate independent of merging and weaving activity; merge areas approximately 500 feet on either side of each onramp juncture; and weave sections, where a merge and diverge area were within close proximity to each other. The study area freeway was divided into nine sections; one weave section (between Northside onramp and Howell Mill off-ramp), three merge sections, and five basic mainline sections.

Information from the each of the three LRFs operating on the overpass locations provided data for assessing the three mainline sections. Data from the Peachtree Battle Road overpass location provided information regarding activity on basic sections. Data from the Howell Mill Road overpass provided information related to merge area activity. Data from the Northside Drive overpass provided information related to the merge section activity.

The five mainline basic freeway sections comprised the largest amount of study area freeway, totaling 3.6 miles. As can be seen in Table 5-7, the modal activity variables for the basic section were relatively consistent for each condition. If anything, the modal activity appeared to increase slightly under metered conditions. This is the opposite of what would be expected considering the intent of ramp metering is to smooth mainline traffic flow.

Table 5-7
Summary of Modal Activity for the Mainline Basic Freeway Sections

Modal Activity Variable	**Mainline Basic Section**	
	Metered	**Non-Metered**
Average Speed (mph)	69.9	69.5
Average Acceleration (mph/sec)	-.52	-.52
Percent of Cycle Acceleration > 3 (mph/sec)	0.6	0.7
Percent of Cycle with Acceleration > 6 (mph/sec)	0.1	.04
Percent of Cycle with Deceleration > 2 (mph/sec)	6.4	4.8
Percent of Cycle with IPS > 90 (mph^2/sec)	4.5	3.3
Percent of Cycle with IPS > 120 (mph^2/sec)	4.4	3.2

Although it is not readily apparent from the modal activity summary statistics, the JASPROD for the basic freeway sections reveal the beneficial effects of ramp metering. As can be seen in Figures 5-22 and 5-23, the modal activity under non-metered conditions is more dispersed (i.e. there is a shorter peak height) and less consistent than under metered conditions.

Figure 5-22
Mainline Basic Freeway Sections under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

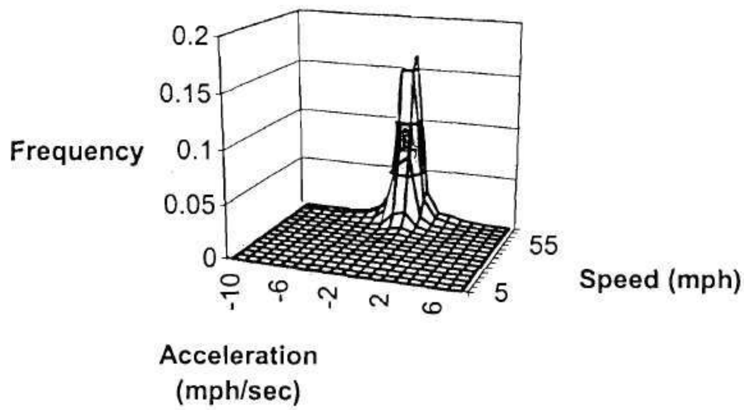
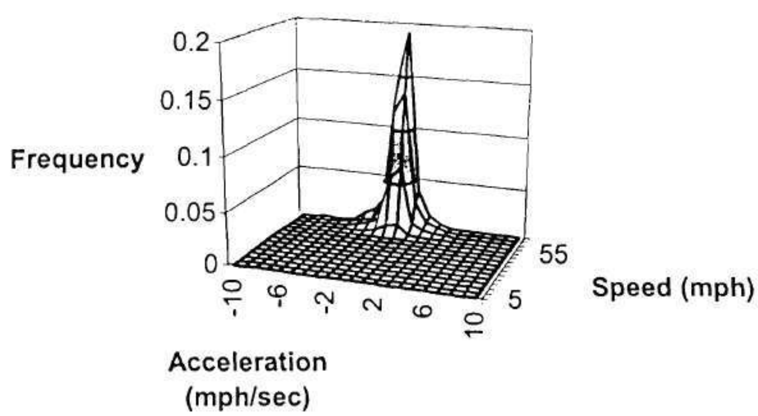


Figure 5-23
Mainline Basic Freeway Sections under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



The three merge areas combined to total 0.6 miles of freeway. As with the basic sections, there does not seem to be a large difference in modal activity between the metered and non-metered conditions. Although, there is was not a large difference in observed activity, the differences consistently move toward an increase in modal activity under non-metered conditions (see Table 5-8). This trend is also apparent in the graphical representation of the modal activity for these sections, shown in Figures 5-24 and 5-25. The modal activity is limited to a narrow region of speed and acceleration combinations, but under non-metered conditions a small amount of activity is apparent in both the high acceleration and deceleration regions. This activity is absent from the metered activity plot, and show the relative impact of the slightly higher engine load and acceleration activity in the merge area under non-metered conditions.

Table 5-8
Summary of Modal Activity for the Mainline Freeway Merge Areas

Modal Activity Variable	**Mainline Merge Area**	
	Metered	**Non-Metered**
Average Speed (mph)	69.6	69.8
Average Acceleration (mph/sec)	-.28	-.26
Percent of Cycle Acceleration > 3 (mph/sec)	1.2	1.8
Percent of Cycle with Acceleration > 6 (mph/sec)	.07	.14
Percent of Cycle with Deceleration > 2 (mph/sec)	4.1	4.3
Percent of Cycle with IPS > 90 (mph^2/sec)	6.3	7.2
Percent of Cycle with IPS > 120 (mph^2/sec)	6.1	7.0

Figure 5-24
Mainline Freeway Merge Area Under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

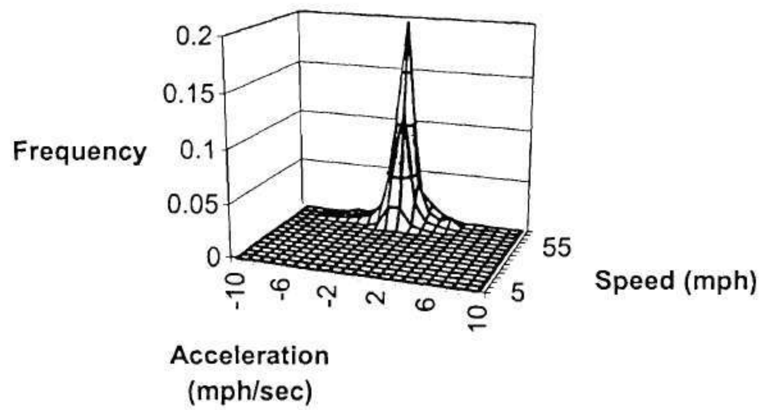
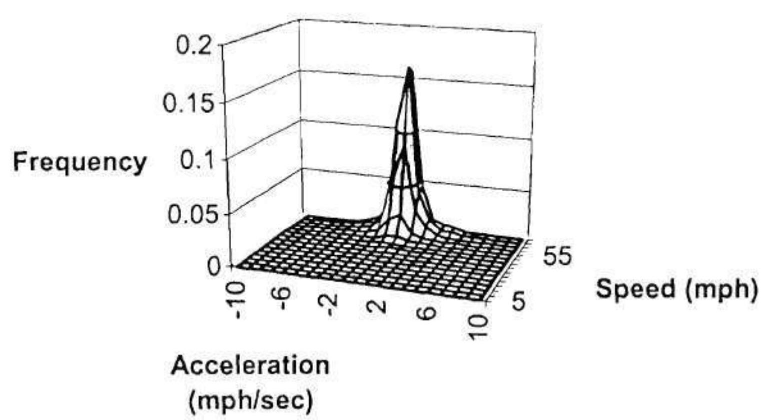


Figure 5-25
Mainline Freeway Merge Areas under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



The weave section consisted of just one, 1000-foot section between the Northside Drive and Howell Mill interchanges. The weave section exhibited much greater changes in modal activity between meted and non-metered conditions when compared to the three mainline sections. Again, the researchers expected that ramp metering would result in smoother mainline operations. However, the field study observed smoother mainline operations on the weave sections under non-metered conditions (see Table 5-9). That is, modal activity in the weave section increased under metered conditions.

Table 5-9
Summary of Modal Activity for the Mainline Weave Area

Modal Activity Variable	**Mainline Weave Area**	
	Metered	**Non-Metered**
Average Speed (mph)	58.1	62.0
Average Acceleration (mph/sec)	-.07	-.04
Percent of Cycle Acceleration > 3 (mph/sec)	1.6	1.2
Percent of Cycle with Acceleration > 6 (mph/sec)	0.2	0.3
Percent of Cycle with Deceleration > 2 (mph/sec)	5.4	2.9
Percent of Cycle with IPS > 90 (mph^2/sec)	12.1	9.0
Percent of Cycle with IPS > 120 (mph^2/sec)	7.4	6.5

The change in modal activity under each condition can be seen in the Watson plots for this section shown in Figures 5-26 and 5-27. Again, these graphs show the possible impact ramp meters have in the weave area by constraining ramp speeds and creating a wider dispersion of activity through the merge area.

Figure 5-26
Mainline Freeway Weave Section under Non-Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)

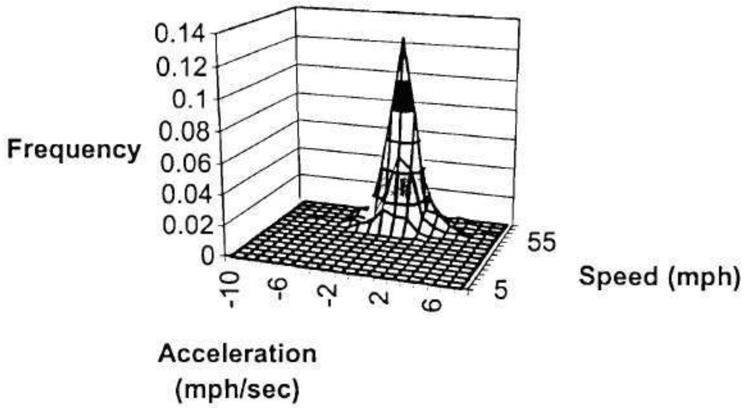
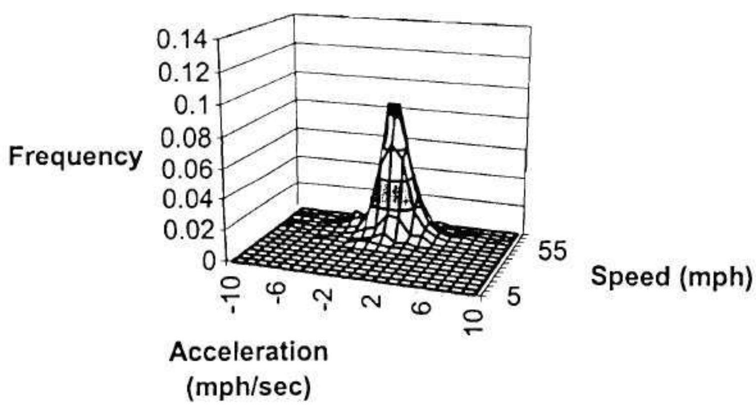


Figure 5-27
Mainline Freeway Weave Section Under Metered Conditions
Joint Acceleration-Speed Probability Density Function (JASPROD)



Information from the probe vehicle runs was used to supplement the LRF mainline data. The probe vehicles provided more comprehensive speed and acceleration data along the mainline section. Table 5-10 summarizes the probe vehicle runs. For comparative purposes, the runs were divided into the same three section types as the LRF data traces.

The probe vehicle data supports the findings from the LRF data discussed above. There appears to be little variation in the level of modal activity between the metered and non-metered conditions. Despite the fact that the difference in modal activity is not large, the small changes in average speed could prove beneficial from an air quality standpoint. Although, the changes in average speed are small, they are consistent (and significant as discussed in the next section) and suggest a slight increase in travel time in the corridor under metered conditions. The decreased travel time will result in fewer seconds of vehicle operations and a possible net reduction in total vehicle emissions.

Table 5-10
Summary of Average Speed Data from Probe Vehicle Runs

	Basic Sections	Merge Areas	Weave Section	Total Section
Metered, Average Speed (mph)	62.4	63.8	63.2	62
Non-Metered, Average Speed (mph)	60.7	61.6	64.4	61
Metered, Average Acceleration (mph/sec)	0.06	0.06	-0.19	0.05
Non-Metered, Average Acceleration (mph/sec)	0.03	0.06	-.059	0.02

5.1.3 Significance of Observed Differences in Modal Activity

The observed differences in modal activity under metered and non-metered conditions demonstrate a clear pattern. Ramp metering systems result in measurable changes in modal activity on onramps. The LRF data were analyzed to determine if the observed differences were statistically significant or simply due to random variations. To accomplish this, a t-test was used to compare the differences in the means of each of the modal variables for metered and non-metered conditions for each onramp location independently. The test was conducted at the 95 percent confidence level. This analysis was limited to an assessment of the LRF data from the onramp acceleration zone locations and an assessment of the average mainline speed measures by the probe vehicles. Although probe vehicles provide information for some of the deceleration zone locations, the sample size was insufficient to perform a statistical analysis in these zones.

The t-test results for the Northside Drive onramp are presented in Table 5-11. All of the means for the modal variables apart from percent of cycle with deceleration greater than 2 mph/sec were found to be statistically significant based on the t-test results. The t-tests for the Howell Mill location shown in Table 5-12 revealed similar results. For this location, all modal variables were found significantly different including percent of cycle with deceleration greater than 2 mph/sec (which was greater under non-metered conditions). This finding is consistent with the results from the Moores Mill location shown in Table 5-13. Again, all tests were significant with the deceleration rate being higher under non-metered conditions. The test results from the West Paces Ferry location, shown in Table 5-14 were not as conclusive. The means for average speed, average acceleration rate, and percent of cycle with acceleration greater than 3mph/sec were significantly different. However, similar conclusions could not be drawn for some of the other modal variables. This notwithstanding, the significance of some variables and the strong evidence from the other locations suggest that ramp metering has a significant impact on onramp modal activity in all cases.

There is little evidence that ramp metering will increase deceleration rates in acceleration zones, and it can be argued that deceleration activity is higher under non-metered conditions. It is clear that deceleration activity will increase in the deceleration zone under ramp metering, but it appears that it will also increase in the acceleration zone as well. This could be the result of higher speeds on the ramp under non-metered conditions. When the meters are not operating, vehicles potentially enter the merge area at speeds higher than mainline speed, requiring a deceleration before the vehicle can enter a gap in the traffic stream. This probably explains the higher modal activity in the freeway weave zone under metered conditions.

One t-test was performed to assess the differences in modal activity observed on the mainline section. The means for the average speed on the mainline under metered and non-metered conditions as measured by the probe vehicles were tested. The observed difference in average speed over the 4.4-mile section was only one mph. As shown in the average metered condition, speed was 62 mph and for the non-metered condition was 61 mph. Given the large data set, the t-test found that these two means were statistically significantly different at 99.5 percent confidence level.

Table 5-11
T-Test Results for Significance in Observed Differences in Modal Activity Changes
Northside Drive Onramp

Modal Activity Variable	Northside Drive					
	Metered Mean	Non-Metered Mean	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	39	40	3.27	1.99	.0016	Yes
Average Acceleration (mph/sec)	3.1	2.8	5.94	1.98	.0000	Yes
Percent of Cycle Acceleration > 3 (mph/sec)	26	11	12.55	1.98	.0000	Yes
Percent of Cycle with Acceleration > 6 (mph/sec)	1.0	0.1	4.97	1.98	.0000	Yes
Percent of Cycle with Deceleration > 2 (mph/sec)	2.2	1.8	1.26	1.99	.2110	No
Percent of Cycle with IPS > 90 (mph^2/sec)	30	21	6.35	1.98	.0000	Yes
Percent of Cycle with IPS > 120 (mph^2/sec)	10.5	6.8	4.99	1.98	.0000	Yes

Table 5-12
T-Test Results for Significance in Observed Differences in Modal Activity Changes
Howell Mill Road Onramp

Modal Activity Variable	Howell Mill Road					
	Metered Mean	Non-Metered Mean	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	36	49	21.23	1.99	.0000	Yes
Average Acceleration (mph/sec)	3.2	1.6	26.81	1.98	.0000	Yes
Percent of Cycle Acceleration > 3 (mph/sec)	29	2.2	27.23	1.98	.0000	Yes
Percent of Cycle with Acceleration > 6 (mph/sec)	2.4	0.01	16.09	1.98	.0000	Yes
Percent of Cycle with Deceleration > 2 (mph/sec)	2.1	4.9	4.55	2.02	.0000	Yes
Percent of Cycle with IPS > 90 (mph^2/sec)	26	6.0	18.33	1.98	.0000	Yes
Percent of Cycle with IPS > 120 (mph^2/sec)	10	2.1	14.87	1.98	.0000	Yes

Table 5-13
T-Test Results for Significance in Observed Differences in Modal Activity Changes
Moores Mill Road Onramp

Modal Activity Variable	Moores Mill Road					
	Metered Mean	Non-Metered Mean	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	34	45	21.48	1.98	.0000	Yes
Average Acceleration (mph/sec)	2.6	1.4	16.45	1.97	.0000	Yes
Percent of Cycle Acceleration > 3 (mph/sec)	16	3.0	16.765	1.97	.0000	Yes
Percent of Cycle with Acceleration > 6 (mph/sec)	2.6	0.2	4.60	1.98	.0000	Yes
Percent of Cycle with Deceleration > 2 (mph/sec)	5.2	8.4	4.39	1.98	.0000	Yes
Percent of Cycle with IPS > 90 (mph^2/sec)	10.5	5.9	5.21	1.98	.0000	Yes
Percent of Cycle with IPS > 120 (mph^2/sec)	5.1	3.0	3.03	1.97	.0028	Yes

Table 5-14
T-Test Results for Significance in Observed Differences in Modal Activity Changes West Paces Ferry Road Onramp

Modal Activity Variable	West Paces Ferry Road					
	Metered Mean	Non-Metered Mean	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	37	44	12.29	1.98	.0000	Yes
Average Acceleration (mph/sec)	1.9	1.4	7.16	1.98	.0000	Yes
Percent of Cycle Acceleration > 3 (mph/sec)	9	4.2	6.78	1.98	.0000	Yes
Percent of Cycle with Acceleration > 6 (mph/sec)	0.7	0.2	1.79	1.98	.0763	No
Percent of Cycle with Deceleration > 2 (mph/sec)	10.9	10.2	0.53	1.98	.5985	No
Percent of Cycle with IPS > 90 (mph^2/sec)	9.2	7.8	1.80	1.99	.0749	No
Percent of Cycle with IPS > 120 (mph^2/sec)	4.3	3.5	1.39	1.98	.1664	No

The observed modal activity patterns for all of the facilities are clearly different under metered and non-metered conditions. The modal variables indicated as being important in the MEASURE Aggregate Modal Model differ significantly across these facilities with and without metering. The question that remains is whether these significant differences in modal activity on the onramps and mainline will result in a small or large emissions increases or decreases. The emissions modeling estimates for the ramp metering system are discussed in the next section.

5.2 Emissions Estimates

As discussed in Chapter 2, changes in modal activity and related engine operations will impact vehicle emission rates. In general, hydrocarbon (HC) and carbon monoxide (CO) emissions are more sensitive to enrichment and changes in modal activity. Emissions estimates presented here will be for HC, and oxides of nitrogen (NOx), both important pollutants with respect to ozone formation. The I-75 ramp system studied by the research team had a significant impact on modal vehicle activity and, in most cases, meter operation increases emissions-related modal activity. Ramp meters, by the nature of operation, induce a hard acceleration load when vehicles stop at the meter and then accelerate to freeway speeds. In addition, when meters provide improved flow on the mainline freeway segments, engine loads can increase as well.

The mass emissions predictions presented in this Chapter are the product of measured vehicle activity and model-predicted emission rates. The research team measured vehicle activity in the field using laser guns and probe vehicles, as described in Chapter 4. Emission rates appropriate to the observed vehicle activity were predicted using the MEASURE Aggregate Modal Model and the MOBILE5b average speed model (described in Chapter 3).

5.2.1 MEASURE Aggregate Modal Model Estimates

Emissions estimates were produced from the MEASURE Aggregate Modal Model for each pollutant using the observed speed/acceleration activity profile and vehicle fleet technology information from each ramp and mainline location. The emission rates were produced for each 15-minute period of each data collection day and applied to the observed volumes in those time periods. The estimated mass emissions were then aggregated and averaged to provide emissions estimates for typical metered and non-metered conditions. Table 5-15 presents the MEASURE Aggregate Modal Model gram/second emissions rates for HC and NOx by location for metered and non-metered conditions.

Table 5-15
Summary of MEASURE Aggregate Modal Model Emissions Rates

Location	Emissions Rates Metered Conditions (grams/sec)		Emissions Rates Under Non-Metered Conditions (grams/sec)	
	HC	NOx	HC	NOx
Northside Drive	.005454	.00931	.005429	.01341
Howell Mill Road	.005421	.01065	.005445	.01906
Moores Mill Road	.005431	.01044	.005448	.01776
West Paces Ferry Road	.005462	.01068	.005440	.01566
Mainline	.005764	.05839	.005982	.05642

The HC gram/second emissions rates for the onramp locations remain consistent under metered conditions. However, because ramp meters result in lower average ramp speeds, the number of seconds of operation under metered conditions are greater, and net HC emissions will increase. The NOx emissions rates for the onramps were consistently lower under metered conditions, due to a decrease in average engine load along the entire ramp. On the mainline freeway segments, HC emissions rate for the mainline freeway were predicted to decrease under metered conditions due to smoother traffic operations. However, The NOx emissions rates were slightly higher for the mainline location, resulting from the net increase in engine load. On mainline segments, even small changes in emissions rates can yield large increases in total daily mass emissions, given the large freeway traffic volumes.

Mass emissions estimates are a function of observed vehicle activity (speed/acceleration characteristics and traffic volumes) during the data collection periods and appropriate emission rates. However, traffic volumes were slightly lower during the non-metered days. Thus, applying predicted emissions rates to the observed traffic volumes would yield mass emissions estimates that are not comparable between metered and non-metered days. For an accurate comparison of metered and non-meted conditions, researchers needed to hold traffic volumes constant across analyses. This way, emissions analysis would isolated the effect of changes in modal activity and average speed resulting from ramp meter operation. Researchers predicted mass emissions for the 2.75-hour peak evening period of an average day, with traffic volumes held constant across analyses. The HC and NOx mass emissions estimates for the four onramps for are shown in Figures 5-28 and 5-29. Mainline and system wide HC and NOx mass emissions estimates for metered and non-metered conditions are provided in Figures 5-30 and 5-31.

Figure 5-28
MEASURE Hydrocarbon Mass Emissions Estimates for Onramp Locations
Traffic Volume Held Constant

Figure 5-29
MEASURE Oxides of Nitrogen Mass Emissions Estimates for Onramp Locations
Traffic Volume Held Constant

Figure 5-30
MEASURE HC Mass Emissions Estimates for Mainline Traffic and System Total
Traffic Volume Held Constant

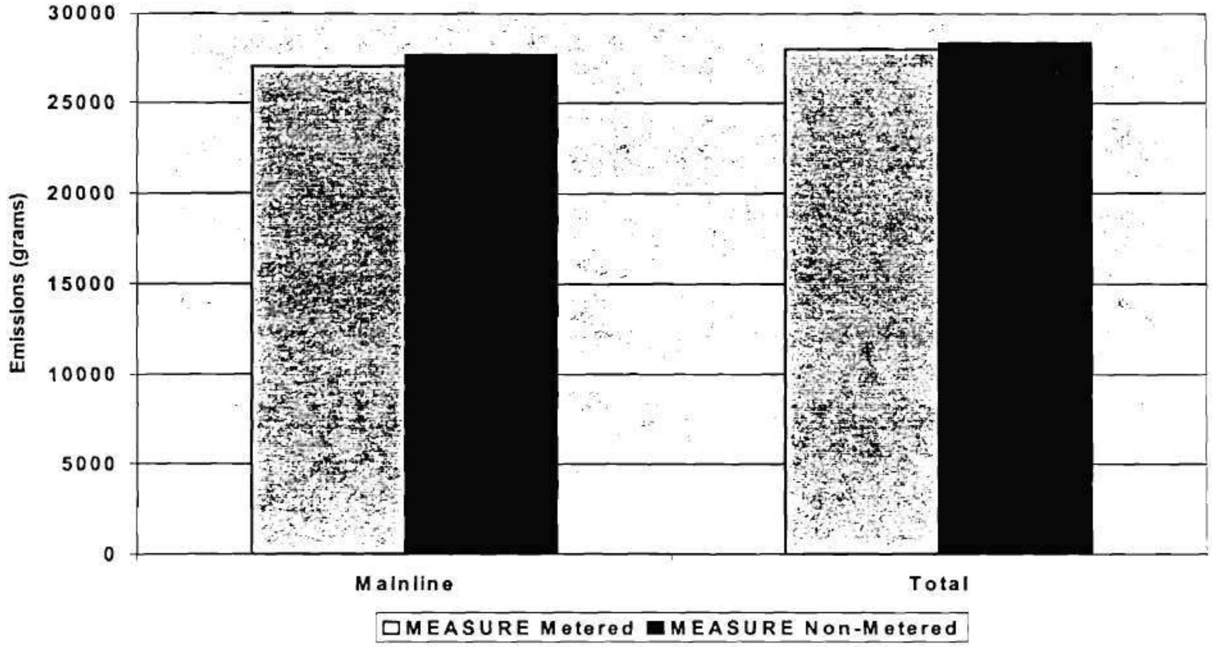
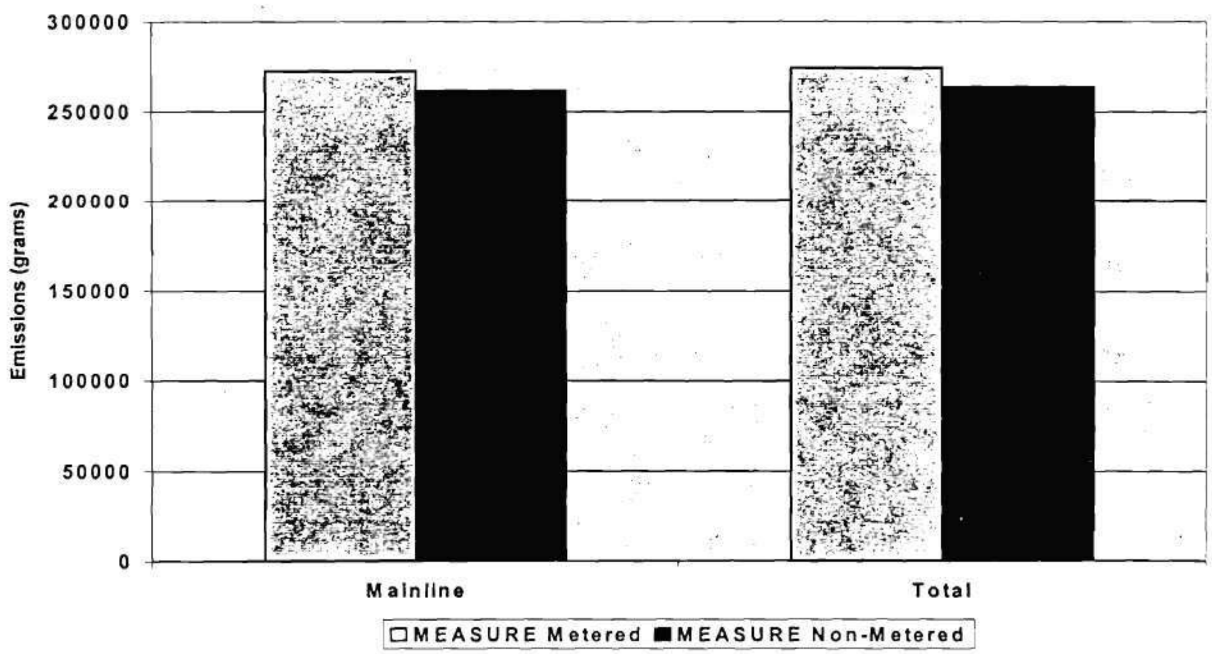


Figure 5-31
MEASURE NOx Mass Emissions Estimates for Mainline Traffic and System Total
Traffic Volume Held Constant



Under volume-controlled conditions, HC mass emissions estimates for all four onramps rise significantly under metered conditions. The HC emissions increase range from 40 to 46% under metered conditions, due to a slight increase in emission rates and extended operating times on the ramps. The opposite trend at ramps was apparent for estimated NOx emissions associated with onramp activity. NOx emissions estimates were lower under metered conditions for all four ramp locations. While Northside drive ramp emissions dropped by only a few percent, reductions at the other ramps ranged from 12 to 22% under metered conditions.

The onramp emissions estimates are important, but the mainline emissions for the studied ramp system have a much greater impact on the overall system evaluation. The mainline segments here account for 96 to 98 percent of the system wide emissions. The volume-controlled HC emissions analysis for the mainline section showed a 2% decrease in mass emissions under metered conditions. Total system wide HC emissions were lower by about 1% on a typical metered day, due to the emissions increases at the ramps. The emissions estimates for NOx under volume-controlled conditions showed an increase in mainline NOx emissions of approximately 4% under metered conditions. System wide NOx emissions also increased by approximately 4% because the ramp emissions decrease was insignificantly small compared to the mainline emissions increase. Table 5-16 provides a complete summary of the volume-controlled mass emissions estimates for an average day, over the 2.75-hour evening peak period.

Table 5-16
Summary of MEASURE Aggregate Modal Model Mass Emissions Estimates
Traffic Volumes Held Constant

Location	HC Mass Emissions Under Non-Metered Conditions (grams)	HC Mass Emissions Under Metered Conditions (grams)	Metering Effect
Northside Drive	266	388	46%
Howell Mill Road	148	215	45%
Moores Mill Road	150	200	33%
West Paces Ferry Road	108	140	30%
Mainline	27,688	27,054	-2%
Total	28,359	27,997	-1%

Location	NOx Mass Emissions Under Non-Metered Conditions (grams)	NOx Mass Emissions Under Metered Conditions (grams)	Metering Effect
Northside Drive	680	664	-2%
Howell Mill Road	533	420	-21%
Moores Mill Road	489	379	-22%
West Paces Ferry Road	327	288	-12%
Mainline	261,614	272,517	4%
Total	263,643	274,268	4%

5.2.2 MOBILE5b Model Estimates

To produce emissions estimates that would be directly comparable with the MEASURE Aggregate Modal Model analysis, the same operating parameters were used in MOBILE5b analysis. As with the previous analyses, traffic volumes were held constant for this analysis. The MOBILE5b mass emissions estimates for HC and NOx for the onramp locations are shown in Figure 5-32 and 5-33. The HC and NOx mass emissions estimates for the mainline section and the total system are shown in Figure 5-34 and 5-35.

Figure 5-32
MOBILE5b Hydrocarbon Mass Emissions Estimates for Onramp Locations
Traffic Volume Held Constant

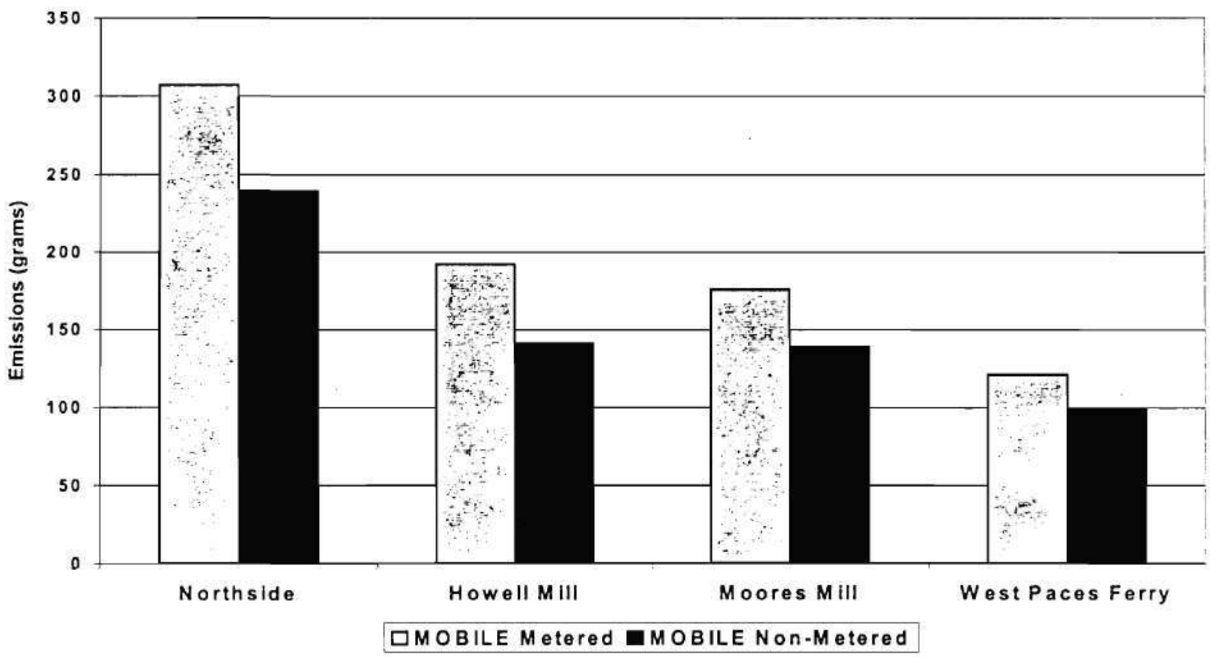


Figure 5-33
MOBILE5b Oxides of Nitrogen Mass Emissions Estimates for Onramp Locations
Traffic Volume Held Constant

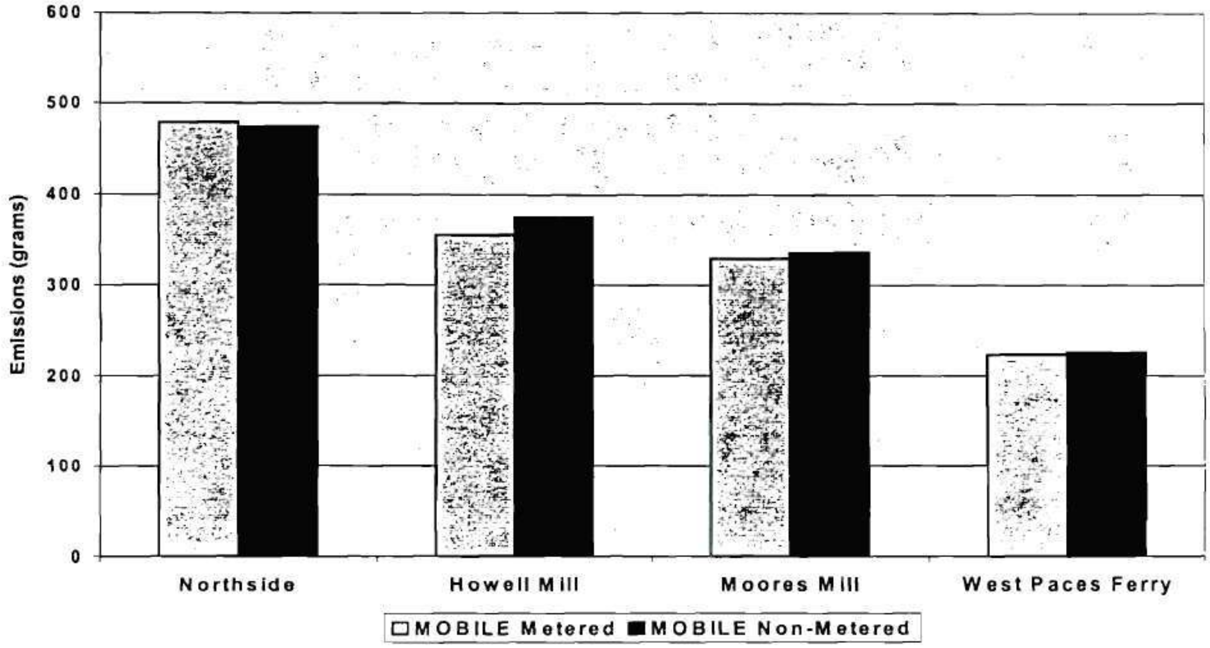


Figure 5-34
MOBILE5b HC Mass Emissions Estimates for Mainline Traffic and System Total
Traffic Volume Held Constant

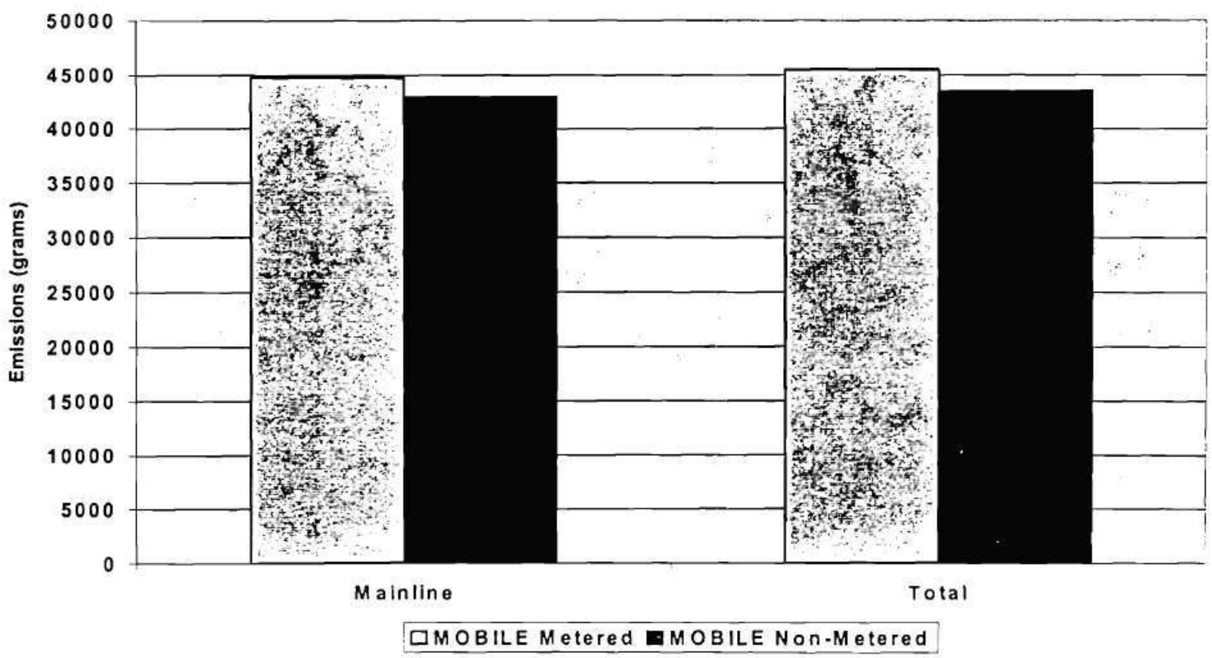
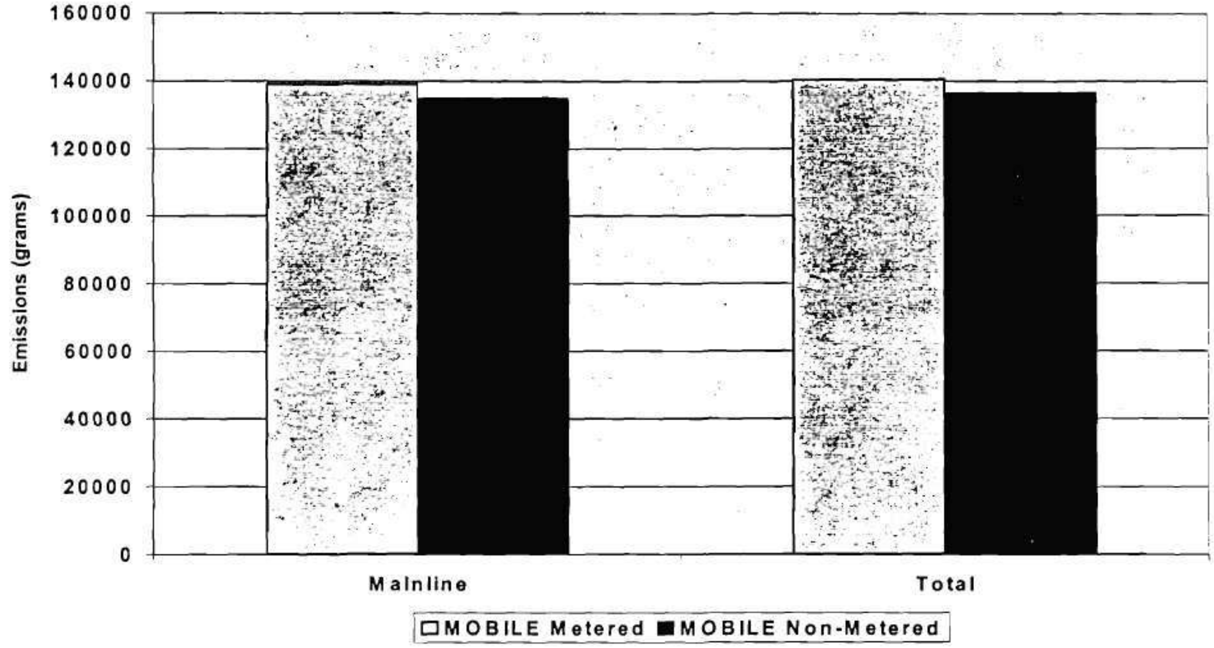


Figure 5-35
MOBILE5b NOx Mass Emissions Estimates for Mainline Traffic and System Total
Traffic Volume Held Constant



The MOBILE5b analyses agree with the direction of the MEASURE Aggregate Modal Model emissions assessments, predicting that HC emissions increase and NOx emissions decrease on ramps under metered conditions (except for Northside drive). Interestingly, mainline HC emissions predicted using MOBILE5b are projected to increase under metered conditions, as well as the system wide total. As with MEASURE Aggregate Modal Model emissions, mainline NOx emissions are also projected to increase under metered conditions for this case.

5.2.3 Comparison of MEASURE Aggregate Modal Model and MOBILE5b Results

Figures 5-36 and Figure 5-37 compare the MOBILE5b and MEASURE Aggregate Modal Model mass emissions estimates for onramp locations by pollutant. Mainline and system wide emissions totals are compared by pollutant in Figures 5-38 and 5-39.

Figure 5-36
Comparison of MOBILE5b and MEASURE HC Mass Emissions Estimates Onramp Locations under Metered and Non-Metered Conditions

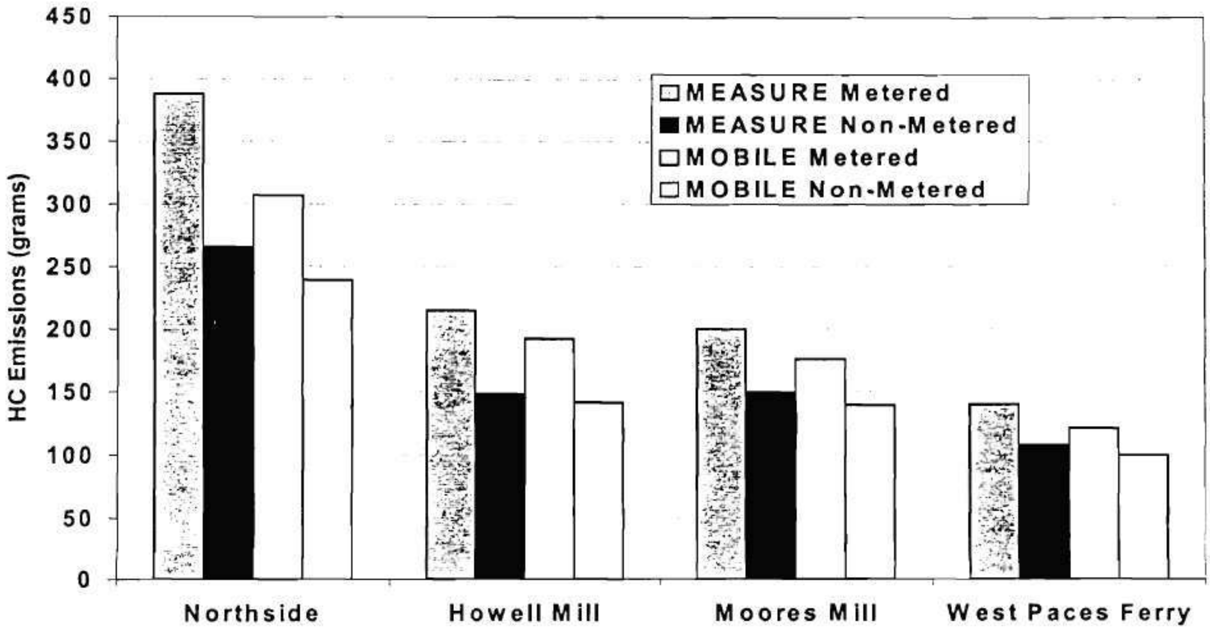


Figure 5-37
Comparison of MOBILE5b and MEASURE NOx Mass Emissions Estimates Onramp Locations under Metered and Non-Metered Conditions

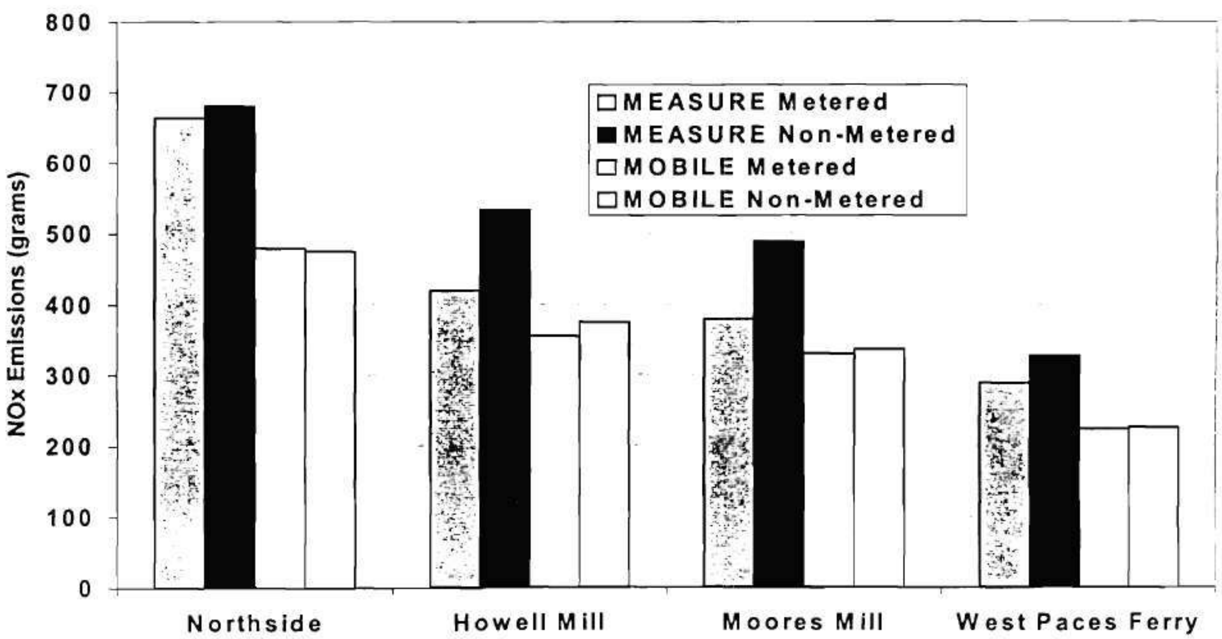


Figure 5-38
Comparison of MOBILE5b and MEASURE HC Mass Emissions Estimates
Mainline and System Total under Metered and Non-Metered Conditions

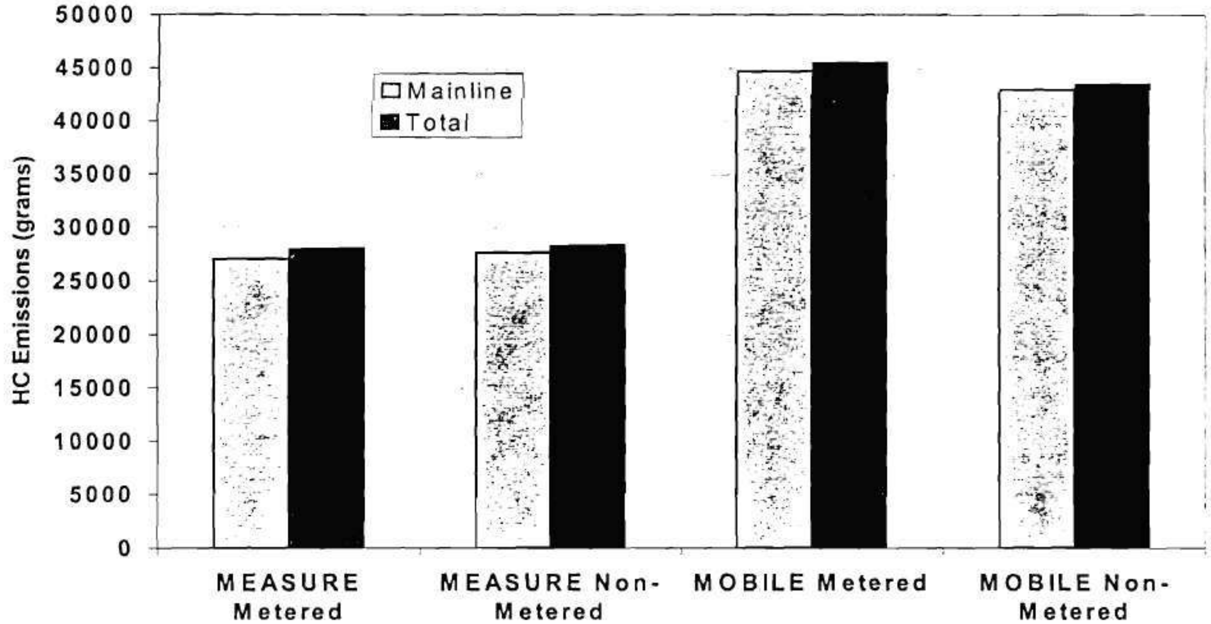
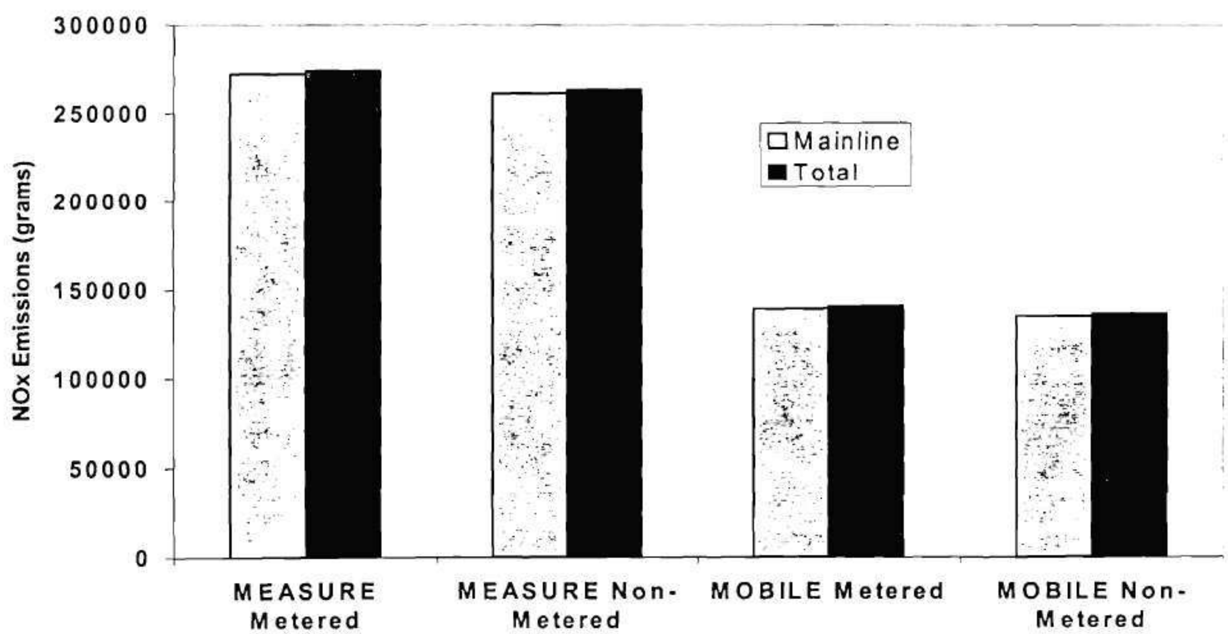


Figure 5-39
Comparison of MOBILE5b and MEASURE NOx Mass Emissions Estimates
Mainline and System Total under Metered and Non-Metered Conditions



The MEASURE Aggregate Modal Model consistently predicts higher HC and NOx emission rates and mass emissions for onramp operations than does MOBILE. Ramp HC emissions for non-metered conditions increased by between 5 and 11% when using the MEASURE model. Ramp HC emissions for metered conditions, however, increased by between 12 and 27% using MEASURE. NOx emissions increased by around 40% for all ramps under non-metered conditions, but increased between 15 and 40% under metered conditions. The MEASURE Aggregate Modal Model and MOBILE6b handle the predicted changes in operating conditions differently. This becomes evident in the MOBILE/MEASURE figures where the emissions change due to changes in onroad driving conditions are more pronounced for the MEASURE Aggregate Modal Model calculations than for MOBILE5b calculations.

The mainline freeway emission rates and mass emissions predicted using the MEASURE Aggregate Modal Model are significantly lower than the mainline freeway HC emission rates and mass emissions predicted using MOBILE5b. The lower MEASURE mainline HC emission rates may reflect lower amounts of enrichment activity observed in the field than occurred in the laboratory tests used to develop the speed correction factors for the MOBILE model. Validation testing of the HC components of the MEASURE Aggregate Modal Model has been performed (Fomunung, et al., 2000) showing better performance than MOBILE5a. Nevertheless, the fact that MEASURE Aggregate Modal Model emissions are projected to be 35% lower than MOBILE5b emissions for the observed mainline conditions has triggered additional validation work at Georgia Tech. This validation work will assess the performance of the HC model routines for these conditions. The research team is conducting this validation work for EPA, outside of the ramp metering study reported here. The difference in the mainline estimates may have resulted from changes in the modal algorithms that arose in the last developed version of the MEASURE Aggregate Modal Model. For the simulation results in the next chapter, researchers fell back to the previous version of the MEASURE Aggregate Modal Model HC emissions modeling algorithms.

The MEASURE Aggregate Modal Model predicts significantly higher mainline freeway NOx emission rates and mass emissions than MOBILE5b. Under non-metered conditions, ramp emissions predicted by MEASURE at all ramps were approximately 40% higher than MOBILE5b emissions. Under metered conditions, ramp emissions predicted by MEASURE at all ramps were between 15 and 40% higher than MOBILE5b emissions. The higher MEASURE Aggregate Modal Model mainline NOx emission rates are driven primarily by average engine load (which corresponds to average speed under cruise conditions). The basic NOx emission rates in the MEASURE Aggregate Modal Model are simply higher than those in MOBILE5b. Again, validation testing of the HC components of the MEASURE model has been performed (Fomunung, et al., 2000) showing better performance than MOBILE5a. Nevertheless, the fact that MEASURE emissions are so different than MOBILE5b is driving additional validation work that is being conducted by the research team outside of the ramp metering study reported here.

5.3 Findings on the Influence of Ramp Design and Prevailing Traffic Conditions

The information presented in section 5.1 showed that there was a clear and significant difference, as expected, in the levels of modal activity between metered and non-metered conditions. It was also evident that there are differences in activity between locations and under different traffic conditions. Part of this research attempts to identify the parameters that may influence modal activity on freeway onramps under metered conditions. The research team selected four parameters with a potential to influence onramp modal activity for further analysis. These included: mainline freeway traffic flow conditions, onramp grade, onramp acceleration distance, and the influence of trucks in the traffic mix. A number of additional factors could potentially impact modal activity, but not all factors could be considered due to the limited number of physical ramp metered locations sampled and the inability to isolate certain factors.

5.3.1 Traffic Volume Effects

As traffic volume on the freeway mainline increases, the ability of vehicles entering the freeway to merge becomes compromised. Indeed, this is one of the main reasons for implementing ramp metering systems. The issue is whether varying traffic conditions influence the level of modal activity at the merge area. To see if this was the case, researchers compared the modal activity data in onramp merge area (i.e. the acceleration zone) under different level of service (LOS) conditions. The Highway Capacity Manual (1998) defines the LOS conditions that range from freeflow "LOS A" conditions to extremely congested "LOS F" conditions. Again, the t-test was the statistical method employed to test the means of the modal activity variables under different levels of service.

It was not possible to test the complete range of traffic conditions (LOS A to F) for differences in modal activity because all levels of traffic operations were not experienced during the data collection phase of this research. The vast majority of traffic conditions observed were at LOS C or D. Field teams never observed any level of service A of F conditions. Some LOS B and E conditions were experienced, but not enough to support a statistical analysis. Therefore, for this analysis changes in modal activity between LOS C and LOS D were tested for each onramp location separately. Independent location tests control for secondary factors such as grade and acceleration distance, which will be discussed in the following sections.

The t-test results for the changes in modal activity between LOS C and D for the Northside Drive Location is presented in Table 5-17. None of the observed differences in modal activity under different LOS were found to be significant for any of the modal variables. This is likely due to the similarity of traffic operations under LOS C and LOS D conditions and not the fact that traffic flow conditions is not an important factor in modal activity. Since these data were associated with a narrow band of traffic conditions with little data associated with light or alternatively highly congested traffic conditions a complete picture of the LOS influences were not detectable. As can be seen in Table 5-18, Table 5-19, and Table 5-20, these findings were consistent for all onramp locations.

Table 5-17
T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the Northside Drive Onramp

Modal Activity Variable	Northside Drive					
	Mean LOS C	Mean LOS D	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	39	39	0.25	1.99	.8073	No
Percent of Cycle Acceleration > 3 (mph/sec)	28.2	25.8	1.21	1.99	.2299	No
Percent of Cycle with Acceleration > 6 (mph/sec)	0.8	0.6	0.72	1.99	.4725	No
Percent of Cycle with Deceleration > 2 (mph/sec)	1.9	1.9	0.007	1.99	.9940	No
Percent of Cycle with IPS > 90 (mph^2/sec)	32	29	1.53	1.99	.1302	No
Percent of Cycle with IPS > 120 (mph^2/sec)	10.4	10.0	1.18	1.99	.2424	No

Table 5-18
T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the Howell Mill Road Onramp

Modal Activity Variable	Howell Mill Road					
	Mean LOS C	Mean LOS D	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	36	36	0.54	1.98	.5861	No
Percent of Cycle with Acceleration > 3 (mph/sec)	28	29	0.70	1.98	.4855	No
Percent of Cycle with Acceleration > 6 (mph/sec)	2.6	2.1	1.56	1.98	.1226	No
Percent of Cycle with Deceleration > 2 (mph/sec)	2.0	2.2	0.36	1.98	.7129	No
Percent of Cycle with IPS > 90 (mph^2/sec)	26	26	0.06	1.98	.9470	No
Percent of Cycle with IPS > 120 (mph^2/sec)	9.9	10.1	0.22	1.98	.8230	No

Table 5-19
T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the Moores Mill Road Onramp

Modal Activity Variable	Moores Mill Road					
	Mean LOS C	Mean LOS D	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	32.5	33.8	2.03	1.99	.0453	Yes
Percent of Cycle with Acceleration > 3 (mph/sec)	15.3	16.5	0.74	1.99	.4588	No
Percent of Cycle with Acceleration > 6 (mph/sec)	1.2	0.82	1.07	1.99	.2846	No
Percent of Cycle with Deceleration > 2 (mph/sec)	7.9	4.5	2.52	2.01	.0149	Yes
Percent of Cycle with IPS > 90 (mph^2/sec)	8.6	9.0	0.43	1.99	.6619	No
Percent of Cycle with IPS > 120 (mph^2/sec)	3.1	3.3	0.43	1.99	.6676	No

Table 5-20
T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the West Paces Ferry Road Onramp

Modal Activity Variable	West Paces Ferry Road					
	Mean LOS C	Mean LOS D	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	35.8	36.3	0.31	2.13	.7629	No
Percent of Cycle with Acceleration > 3 (mph/sec)	9.4	13.0	0.90	2.31	.3937	No
Percent of Cycle with Acceleration > 6 (mph/sec)	0.4	0.4	1.00	2.44	.3548	No
Percent of Cycle with Deceleration > 2 (mph/sec)	13.9	5.5	1.94	2.11	.0687	No
Percent of Cycle with IPS > 90 (mph^2/sec)	8.8	12.9	1.27	2.31	.2403	No
Percent of Cycle with IPS > 120 (mph^2/sec)	3.8	7.5	1.14	2.36	.2902	No

5.3.2 Grade Effects

Roadway grade increases engine load and can lead to enrichment and elevated emissions levels. When possible, freeway onramp designs include negative grade so vehicles entering the freeway can more easily achieve freeway speed. For this same reason, designers avoid positive freeway onramp grades. Hence, onramp designs typically minimize grade-induced enrichment. Despite this, two of the ramps in the study area exhibit a positive grade. To test for grade-influenced vehicle modal activity, the speed/acceleration data from the two positive grade locations were compared with the two negative grade locations under metered conditions. To the extent possible, secondary influences such as truck volumes were controlled in this analysis.

Similar to the other statistical tests used in this research, the t-test was utilized to test the means of the modal activity variables for the positive and negative grade ramps. In all cases, the t-test failed to identify any significant differences in the variable means. This suggests that ramp grade does not have a significant influence on the modal activity of vehicles operating for these freeway onramps under the conditions observed. This is not to say the grade is not an important consideration for onramp design, but that grade did not significantly change modal activity on the observed ramps under the observed traffic conditions.

5.3.3 Acceleration Distance Effects

As with grade, the ideal ramp design includes sufficient acceleration distance so that vehicle can make a smooth transition from the arterial system to the freeway system. If the acceleration zone is too short, drivers will be inclined to accelerate more rapidly to reach the necessary merge speed. Ramp metering systems can compromise the length of the acceleration zone. In other cases, physical constraints do not allow for the optimal acceleration distance. It was hypothesized that modal activity would increase on ramps with short acceleration differences due to the need (or perceived need) to accelerate at a higher rate.

To test for this the data from the short Howell Mill Road onramp (975 feet) was compared with data from the longer Moores Mill Road and West Paces Ferry Road onramps (2000 feet). The acceleration distance for the Howell Mill Ramp is 450 feet. The acceleration distance for the Moores Mill Road and West Paces Ferry Road ramps are approximately 700 to 800 feet. The t-test results for the comparison of the means for the modal variables are presented in Table 5-21. All but one of the modal variables were significantly different between short and long ramps. The short acceleration distance led to significantly increased levels of power-demand-related modal activity. The conclusions are not necessarily transferable to other ramps, since the data were representative of only three onramp locations. More conclusive findings will necessitate the assessment of more ramp locations. However, the potentially significant emissions impacts of short acceleration zones is clearly worthy of more detailed study.

Table 5-21
T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Onramp Acceleration Distance

Modal Activity Variable	Acceleration Distance					
	Mean Short Ramp (975 feet)	Mean Long Ramps (2000 feet)	t-Statistic	Critical t-Value (.05)	t-statistic Probability	Accept Alternative Hypotheses that Means are Different
Average Speed (mph)	37.5	35.5	5.45	1.97	.0000	Yes
Percent of Cycle with Acceleration > 3 (mph/sec)	27.3	12.9	18.18	1.97	.0000	Yes
Percent of Cycle with Acceleration > 6 (mph/sec)	1.5	1.8	0.70	1.97	.4846	No
Percent of Cycle with Deceleration > 2 (mph/sec)	2.2	7.7	9.48	1.97	.0000	Yes
Percent of Cycle with IPS > 90 (mph^2/sec)	27.9	9.9	22.78	1.97	.0000	Yes
Percent of Cycle with IPS > 120 (mph^2/sec)	10.2	4.8	11.12	1.97	.0000	Yes

5.3.4 Effects of Trucks

In theory, the modal activity of individual vehicles on a ramp is dependent upon the actions of other vehicles in the traffic stream. Of particular concern is the presence of trucks and potential for trucks to influence the modal activity of vehicle on the freeway onramps. Truck volumes along the study corridor are not large compared to other freeways in Atlanta. Trucks must obtain a permit to operate in the downtown zone and may not operate on the downtown stretch unless a pick-up or delivery endpoint falls inside the perimeter. To test for the potential influence of truck volumes on mainline and ramp modal activity, the t-text was used to determine whether mean modal activity parameters differed significantly across truck volumes. Modal activity for traffic mix with less than one percent trucks was compared with modal activity for traffic mix greater then two percent trucks. Each site was assessed independently to control for secondary influences. The t-test did not indicate any significant findings regarding modal activity and the presence of trucks at these truck volume percentages for the study corridor. For almost every modal variable tested, the means under the two truck volume conditions were not significantly different. However, this is not surprising given the small truck volumes noted in the traffic stream. In Atlanta freeway corridors, previous studies have indicated that large truck volumes do significantly impact onroad modal operations (Grant, 1997a). The low truck volumes observed in this corridor may actually result in significantly different operating modes than are experienced in other Atlanta corridors. Hence, the research team still believes that future research efforts should explicitly examine the impact of truck volumes on modal operations.

CHAPTER 6
SIMULATION OF THE I-75 RAMP METER CORRIDOR

The field research reported in Chapter 5 indicated that ramp metering on the study corridor does not currently result in significant mainline travel time savings. The emissions modeling results presented in Chapter 5 predicted that operating the ramp meters under the observed traffic flow conditions on the study corridor results in higher mass emissions. However, the presence of a major physical bottleneck upstream of the study section (the I-75/I-85 combined section) constrains the speed, volume, and density conditions of incoming freeway traffic. As such, the field observations cannot examine the potential effect that ramp metering could have if much higher incoming freeway traffic volumes were to occur. Moderate freeway and ramp entry volumes coupled with a long uninterrupted stretch of freeway between the study corridor and heavy downstream congestion (i.e. the I-285 approach) prevented field studies from observing conditions of complete traffic flow breakdown. Given these conditions, even the high volume simulations cannot examine the potential effect that ramp operations may have in delaying the onset of flow breakdown under extreme conditions. This is important because even if ramp metering does not provide emissions benefits under observed conditions or under high flow conditions, metering may still provide emissions benefits if implemented such that the onset of complete flow breakdown is delayed.

By simulating the corridor with a computer simulation tool, researchers can evaluate the effectiveness of the current computer tool for simulating real-world traffic conditions. Researchers can also use the tool to simulate traffic conditions not present during the data collection phase of the project (such as completely congested conditions atypical to this corridor due to an upstream constriction). Simulation runs were developed to examine the potential effect of ramp metering on: 1) observed flow conditions, 2) high traffic flow conditions that were never observed in the field, and 3) a lane closure event designed to result in a simulated traffic flow breakdown (which also was never observed in the field).

To examine potential benefits of ramp metering under conditions that were never observed in the field, simulation modeling was performed under theoretical conditions of: 1) observed flow conditions (to serve as a baseline), 2) high mainline freeway entry volumes, 3) a peak-hour (5:00 p.m. until 6:00 p.m.) lane closure under observed conditions designed to result in traffic flow breakdown, and 4) a peak-hour lane closure under mainline high freeway entry volumes also designed to result in traffic flow breakdown.

6.1 CORSIM Overview

Over the last decade, the Federal Highway Administration has sponsored development of a simulation model known as *Traffic Software Integrated System* (TSIS). This evolving computer program includes a freeway component known as FRESIM, an arterial street module known as NETSIM, and a corridor simulation tool that combines FRESIM and NETSIM into a single analysis program called CORSIM. In addition, the TSIS suite of programs includes a simulation viewer tool named TRAFVU. Because CORSIM permits evaluation of surface streets, ramp-metered conditions, and freeways, the Georgia Tech research team elected to model the I-75 Northbound corridor with CORSIM.

The components of CORSIM collectively use a link-node configuration where road segments are defined as one-way links (i.e. two links are therefore required to identify a two-way road), and nodes identify the extreme end of each link. Unique "interface nodes" are provided at locations where vehicles can transfer from the FRESIM (freeway) environment to the NETSIM (surface street) environment (or similarly from NETSIM to FRESIM). Nodes at the extreme limits of the simulated region are defined as entry and exit nodes.

CORSIM simulation files can be crafted to represent time periods typical of actual traffic fluctuations during a peak period. Anytime a physical geometric feature changes (such as the addition of a lane), a "dummy" node can be included in the simulation file to accommodate the modification. In the NETSIM environment, the analyst can simulate both pre-timed and actuated traffic signals, define specific turning volumes, heavy vehicle distributions, and right-turn-on-red characteristics. The CORSIM environment accommodates lane additions and lane drops, advanced warning signs, and ramp meters. In June 1999, the release of Version 4.3 also included the ability to model high occupancy vehicle (HOV) lanes. The simulation runs for this project include the new TSIS HOV feature because the simulated section contains an HOV facility.

In the CORSIM simulation runs, the program loads the corridor with vehicles of a volume representative of the beginning of simulation and then reaches "equilibrium" before beginning the requested simulation. This way, when the simulation of analysis initiates there are already vehicles on the road as one would expect for a real road. Similarly, upon completion of the simulation, several vehicles will be "stranded" on the road at conclusion of the analysis.

6.2 Experimental Design

To ensure simulation analysis for possible "key" traffic scenarios, the following simulation strategies were developed and analyzed. These included:

- Observed flow with ramp meters inactive
- Observed flow with ramp meters active
- Projected high flow conditions with ramp meters inactive
- Projected high flow conditions with ramp meters active
- Observed peak-hour flows with ramp meters inactive
- Observed peak-hour flows with ramp meters active
- Observed peak-hour flows with a peak-hour lane closure and ramp meters inactive
- Observed peak-hour flows with a peak-hour lane closure and ramp meters active

CORSIM uses random seed generators for simulation. Consequently, to assure statistical representation of the subject corridor, researchers must perform multiple simulations with different random seeds assigned for each simulation. For each of the scenarios examined, the research team generated thirty simulation runs.

To properly simulate a corridor using CORSIM, the Georgia Tech team developed a link-node diagram that represented the geometry of the subject corridor. Similarly, the research team developed an analysis file (*.trf) that included traffic volumes, distributions, traffic signal information, ramp meter information, and turning percentages. The four freeway interchanges located within the project limits are depicted in Figures 6-1 to 6-4 and represent (from south to north) Northside Drive, Howell Mill Road, Moores Mill Road, and West Paces Ferry Road. The links between the interchanges represent mainline freeway segments. The figures overlay the link-node diagram on an aerial photograph for each site, illustrating that the simulation regime includes only the freeways, ramps, and road links critical to the I-75 Northbound conditions.

Figure 6-1
Northside Drive at I-75 Northbound

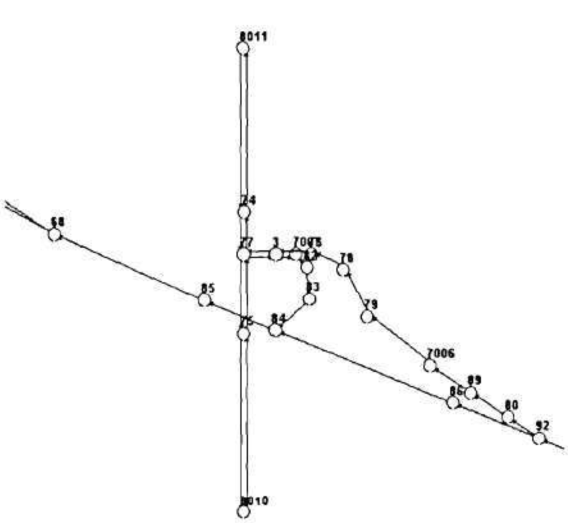
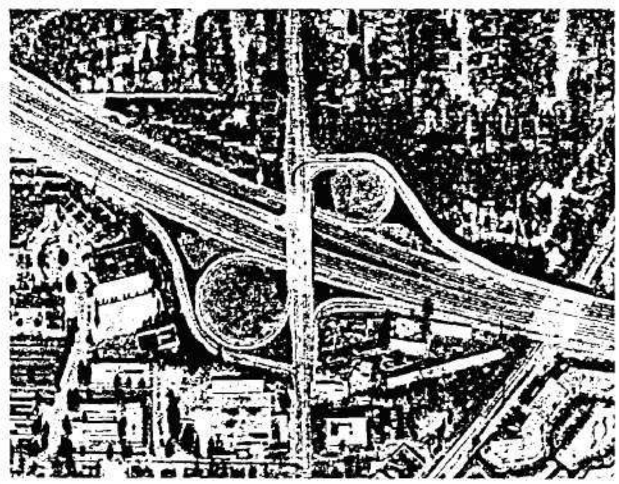
Link-Node Diagram	Aerial Photograph
	

Figure 6-2
Howell Mill Road at I-75 Northbound

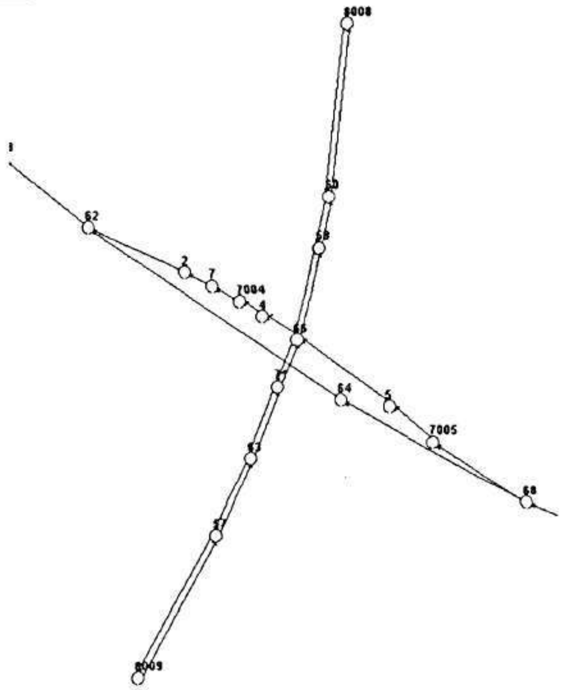
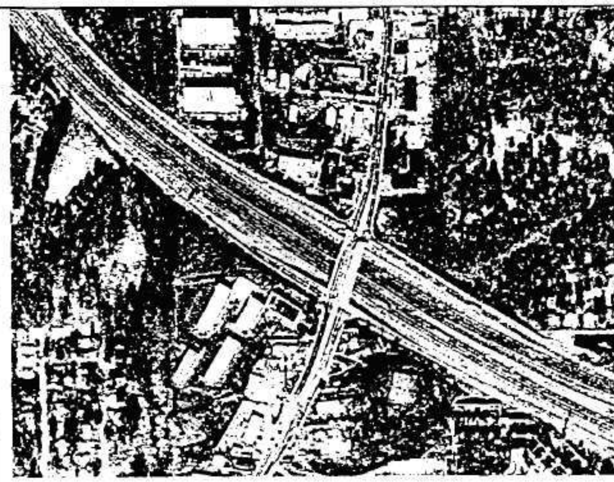
Link-Node Diagram	Aerial Photograph
	

Figure 6-3
Moores Mill Road at I-75 Northbound

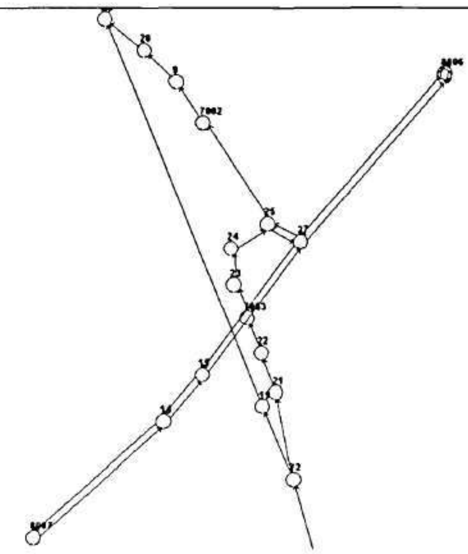
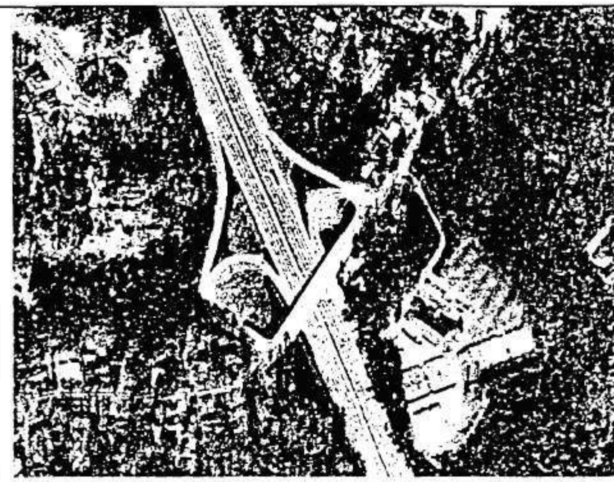
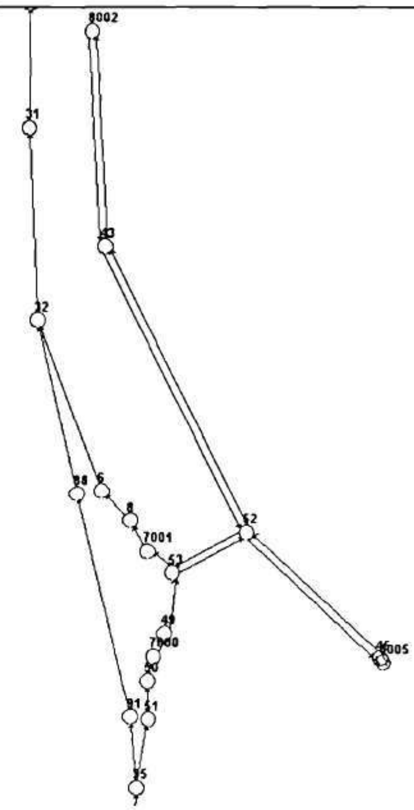
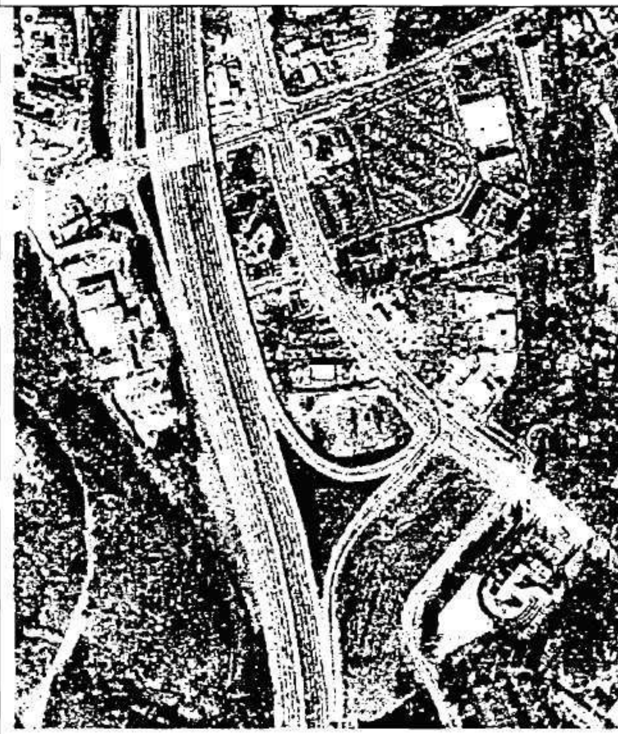
Link-Node Diagram	Aerial Photograph
	

Figure 6-4
West Paces Ferry Road at I-75 Northbound

Link-Node Diagram	Aerial Photograph
	

6.3 Ramp Metering Assumptions

For the observed flow and high flow simulation runs, the research team simulated corridor and ramp meter operation for an afternoon peak period. A ramp meter is located at each onramp for the four interchanges depicted in Figures 6-1 to 6-4. Specifically, the ramp meter occurred at nodes "83", "2", "28", and "6" for Northside, Howell Mill, Moores Mill, and West Paces Ferry Road respectively in the link-node diagram. The ramp meters were assigned clock-time metering (indicating a pre-timed meter assignment independent of observed traffic flow) with a metering headway of 4 seconds. This traffic assignment assumes one vehicle per green, per lane, with assumed 5 percent noncompliance.

Figure 6-5 illustrates the mainline freeway entry volumes for the observed and high volume simulations. Variations in the observed flow values are based upon actual observed flows from a typical data collection day. In the high flow example, mainline freeway volumes were set at the maximum allowed in the simulation given the physical structure of the corridor and model limitation (500 vehicles/5-minutes).

Figure 6-5
Mainline Freeway Simulation Flowrates
Peak Period Observed and High Volume Simulations

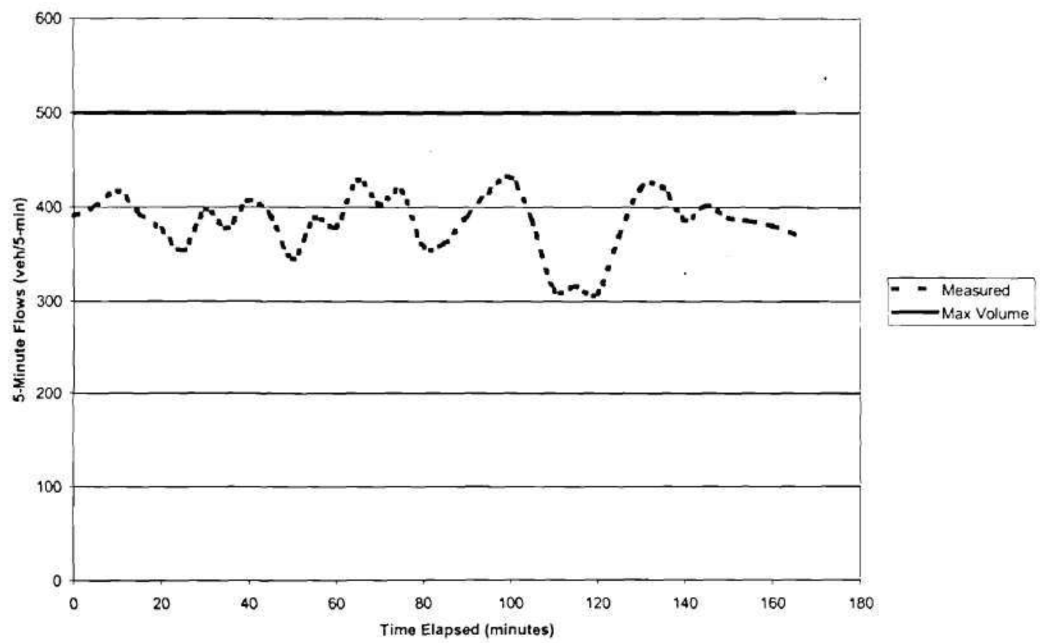
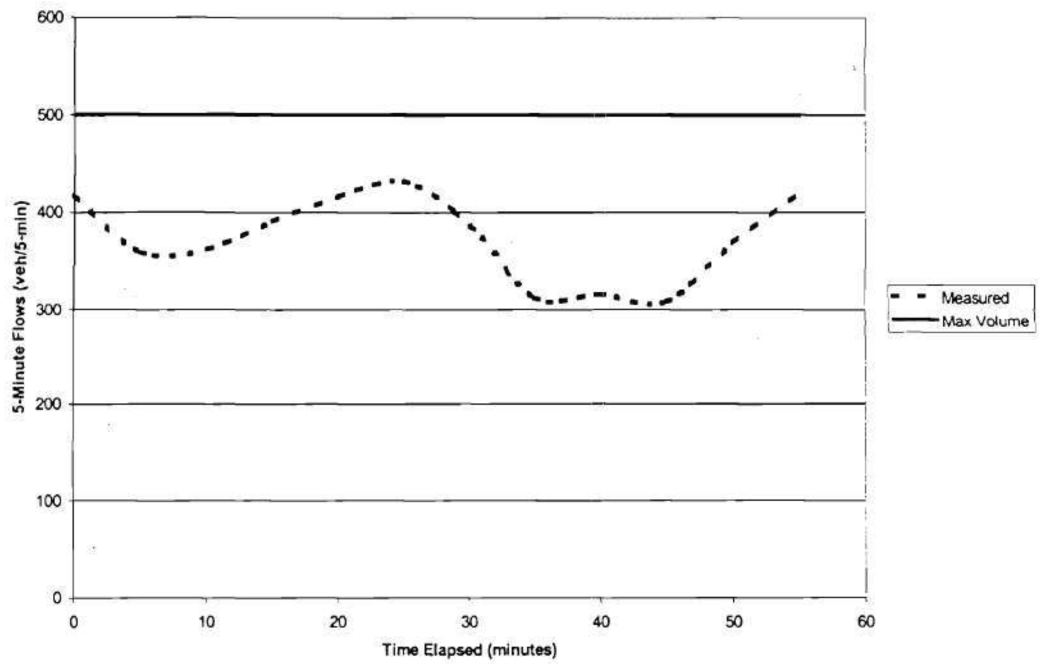


Figure 6-6 contains the mainline freeway entry volumes for the peak period lane closure simulation under both observed and high volume simulations. Appendix D contains the approximate 5-minute volumes used for each entry node (where vehicles enter the simulated corridor) in each simulation. These tables include details for both the observed volume simulations as well as the volumes expected to occur in the simulation when freeway input volumes were maximized (high volume simulations).

Figure 6-6
Mainline Freeway Simulation Flowrates
Peak-Hour Lane Closure Simulations (Observed and High Flow)



6.4 Observed and High Flow Simulation Results (Measures of Effectiveness)

Table 6-1 summarizes the measures of effectiveness for each scenario based upon 30 simulation runs for each scenario. As expected, mainline delay is slightly lower under metered conditions, while ramp and arterial streets (NETSIM analysis) experience greater delay.

Table 6-1
Summary of Measures of Effectiveness for Metered and Non-Metered Conditions
Simulations of Observed and High Flow Scenarios

Table Values Represent the Average Estimate based on 30 CORSIM Simulation Runs	**Non-Metered Observed Flows**	**Metered Observed Flows**	**Non-Metered High Flow**	**Metered High Flow**
Vehicle-Miles Traveled:				
Total Corridor	111,254	107,095	115,877	113,605
NETSIM Total	4,700	3,979	4,755	4,049
FRESIM Total	106,554	103,116	111,122	109,556
Mainline Total	105,245	102,067	109,795	108,483
Ramp Total	1,309	1,049	1,327	1,073
Vehicle-Hours Move Time:				
Total Corridor	1,677	1,612	1,749	1,708
NETSIM Total	154	130	155	132
FRESIM Total	1,523	1,482	1,593	1,576
Mainline Total	1,505	1,455	1,572	1,549
Ramp Total	20	27	20	28
Vehicle-Hours Delay Time:				
Total Corridor	815	1,451	1,361	1,567
NETSIM Total	172	919	177	923
FRESIM Total	643	532	1,184	644
Mainline Total	632	435	1,174	546
Ramp Total	10	98	10	98
Total Vehicle-Hours				
Total Corridor	2,492	3,063	3,110	3,275
NETSIM Total	326	1,049	332	1,055
FRESIM Total	2,166	2,014	2,777	2,220
Mainline Total	2,137	1,890	2,746	2,095
Ramp Total	30	125	30	126

Table 6-2 presents the means and standard deviations of speeds under metered versus non-metered observed flow conditions (additional measure of effectiveness). Figure 6-7 graphically represents the speed distributions for ramps and freeways under metered versus non-metered observed flows conditions. Table 6-3 and Figure 6-8 provide similar information for high-flow (congested) conditions. Figures 6-9 to 6-20 illustrate the speed/acceleration operating profiles predicted by the simulation model for each modeled scenario.

Table 6-2
Speed Comparison of Metered and Non-Metered Conditions for Observed Flows

Runs = 30	Ramp Speeds		Freeway Speeds	
	Meter On	Meter Off	Meter On	Meter Off
Mean (mph)	8.4	44.2	54.0	49.3
Std. Dev. (mph)	0.08	0.11	0.33	0.95

Figure 6-7
Speed Comparison of Metered and Non-Metered Conditions for Observed Flows

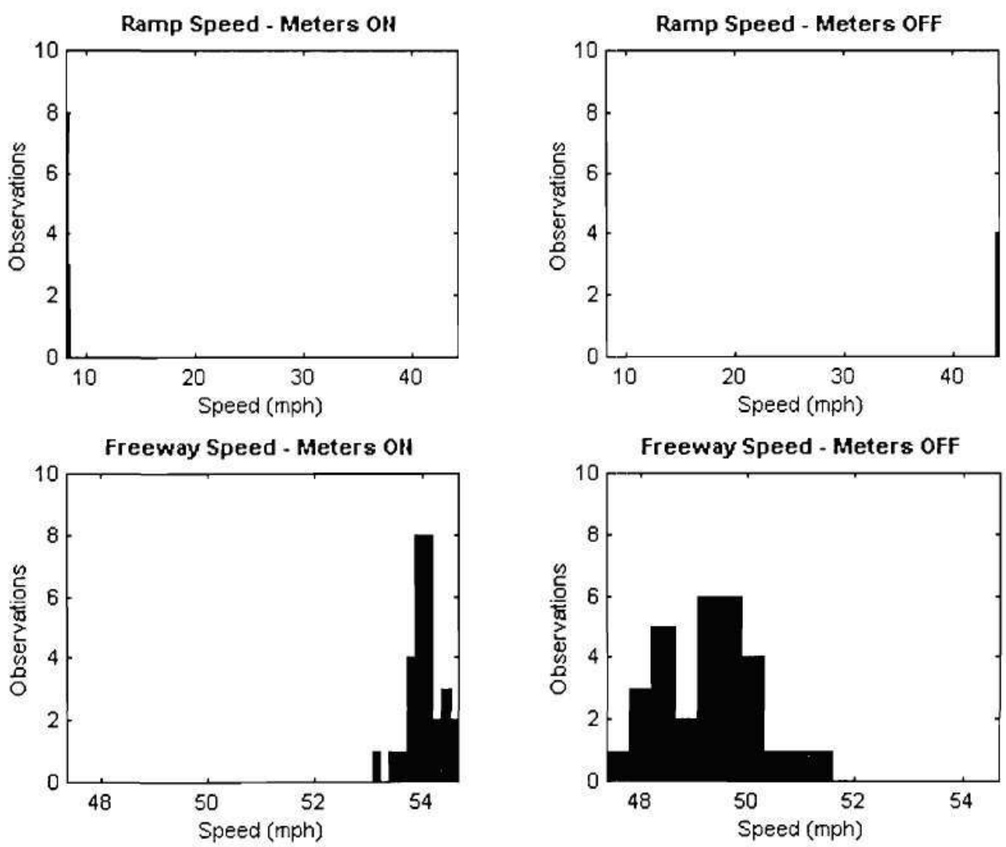


Table 6-3
Speed Comparison of Metered and Non-Metered Conditions at High-Flow

Runs = 30	**Ramp Speeds**		**Freeway Speeds**	
	Meter On	Meter Off	Meter On	Meter Off
Mean (mph)	8.5	43.6	51.8	40.0
Std. Dev. (mph)	0.08	1.02	0.46	1.38

Figure 6-8
Speed Comparison of Metered and Non-Metered Conditions at High-Flow

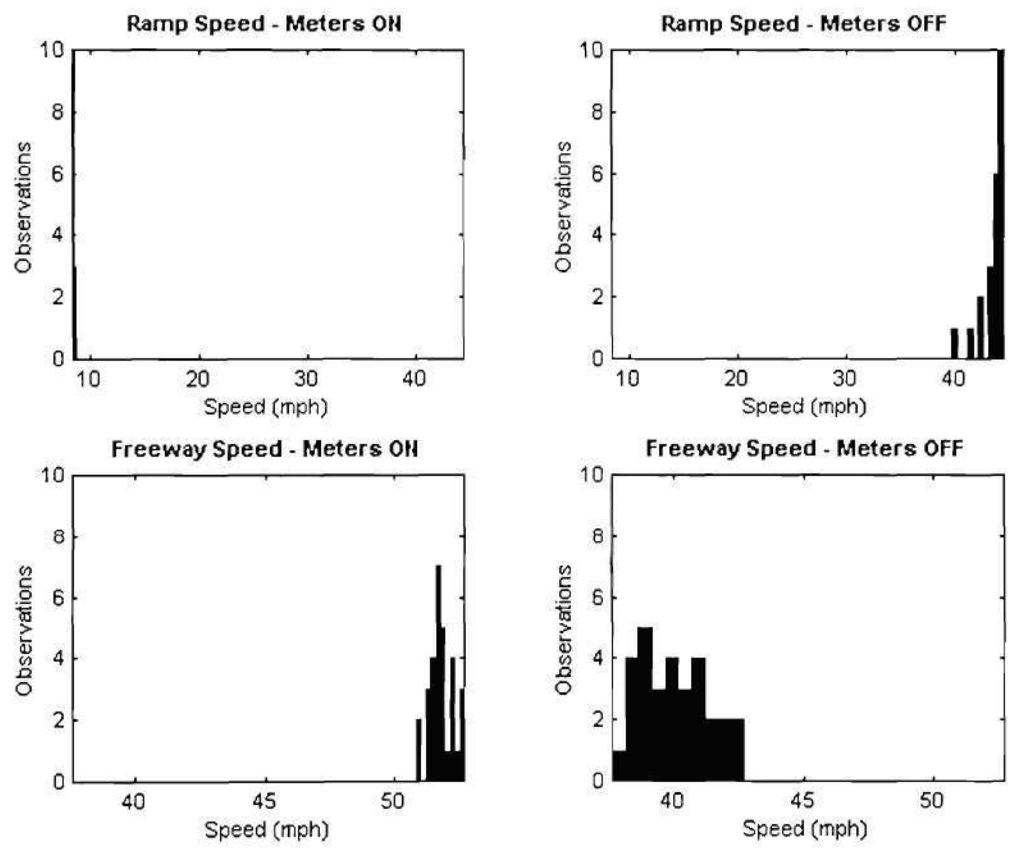


Figure 6-9

Simulated Ramp Operations under Non-Metered Observed Flow Conditions
Watson Plot (Speed vs. Acceleration)

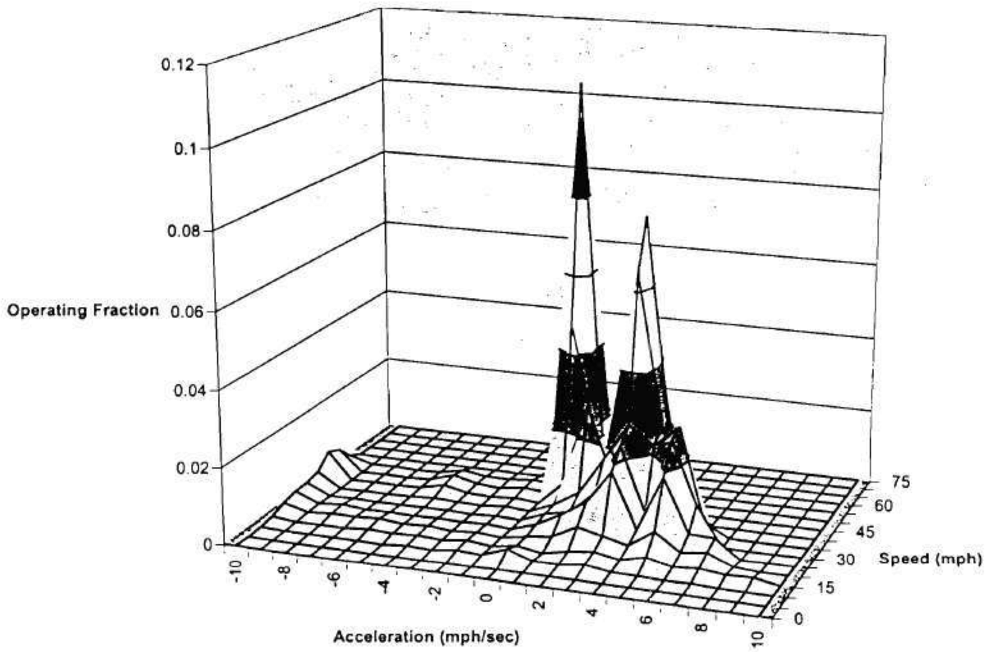


Figure 6-10

Simulated Ramp Operations under Metered Observed Flow Conditions
Watson Plot (Speed vs. Acceleration)

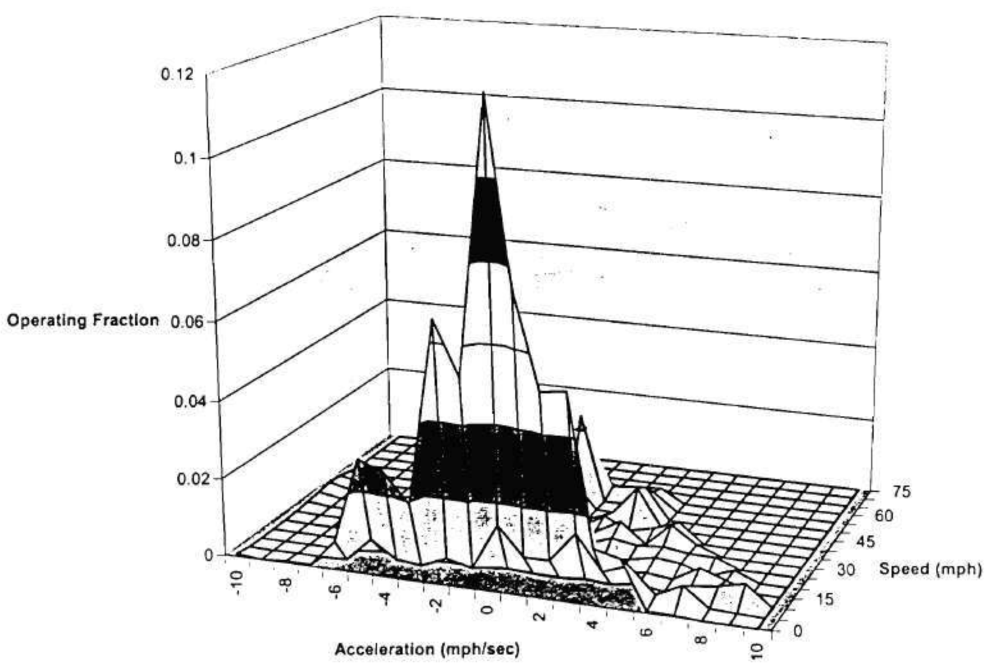


Figure 6-11

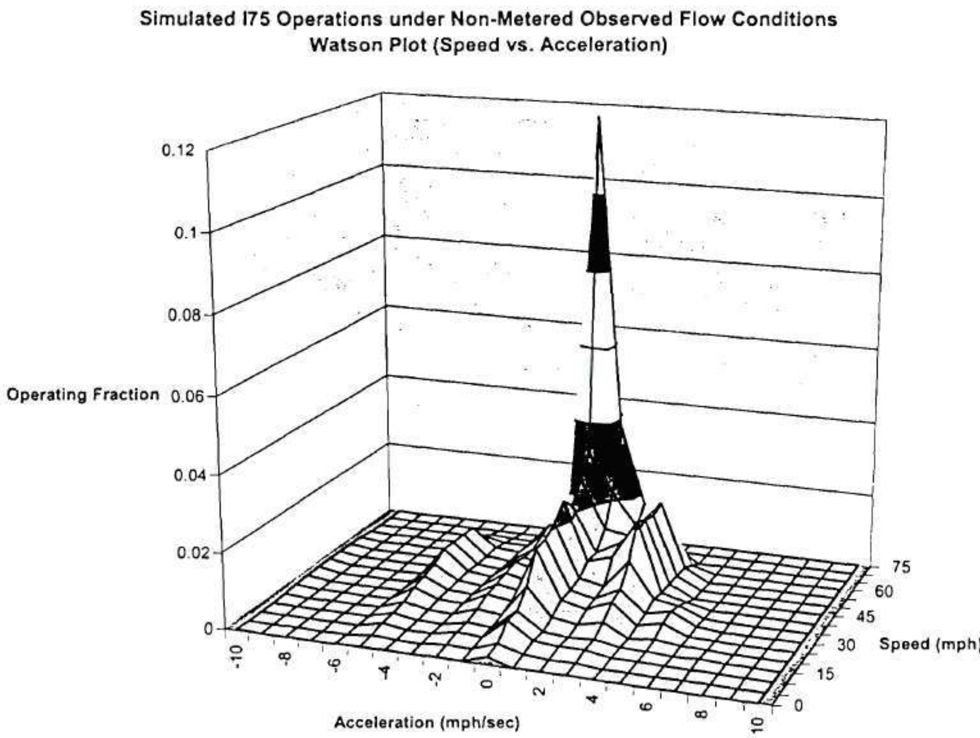


Figure 6-12

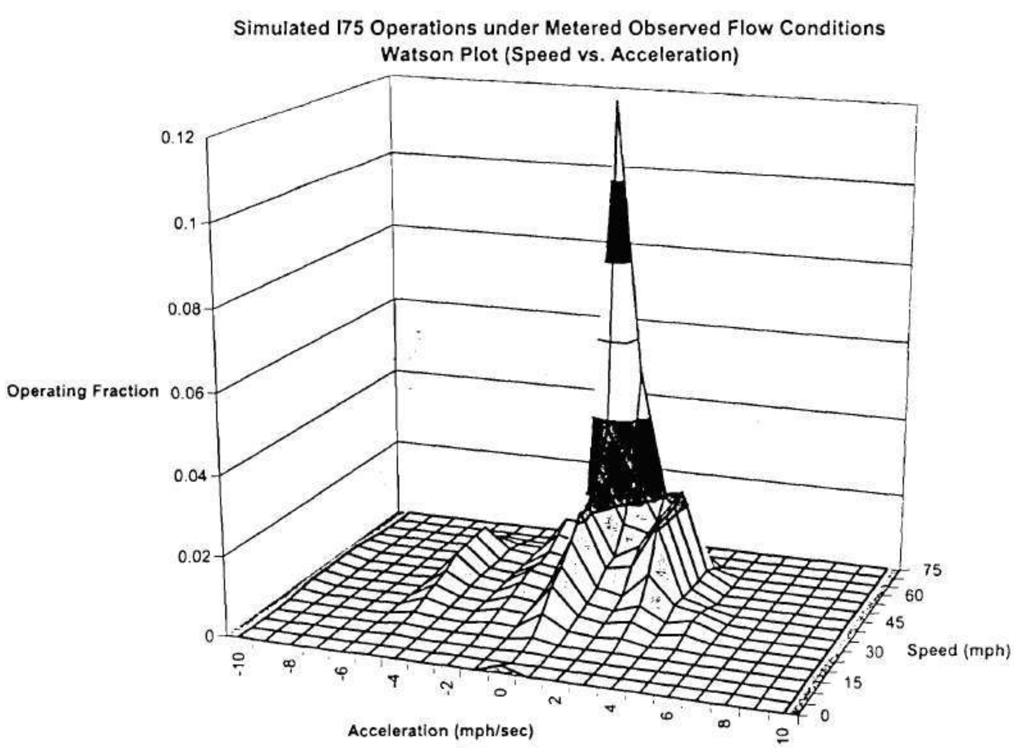


Figure 6-13

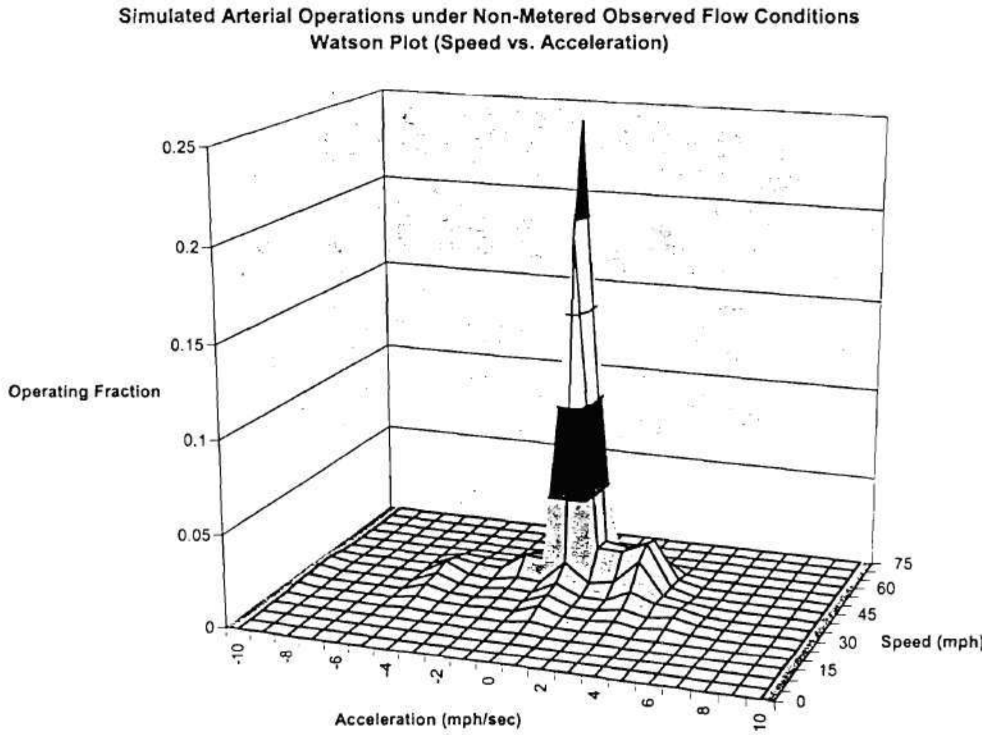


Figure 6-14

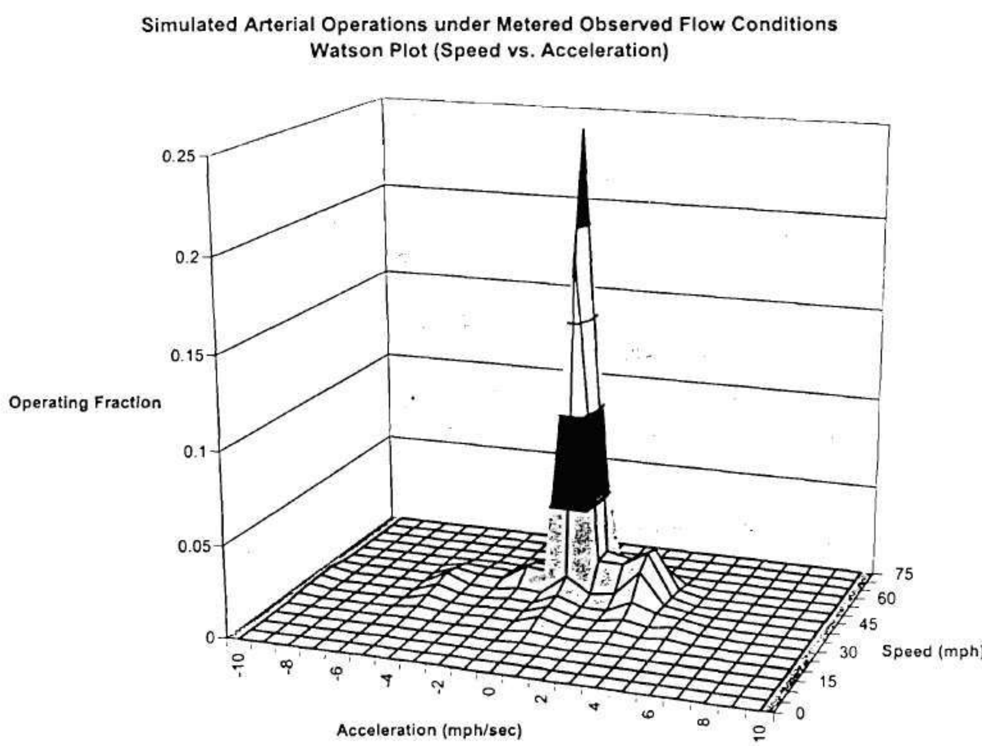


Figure 6-15

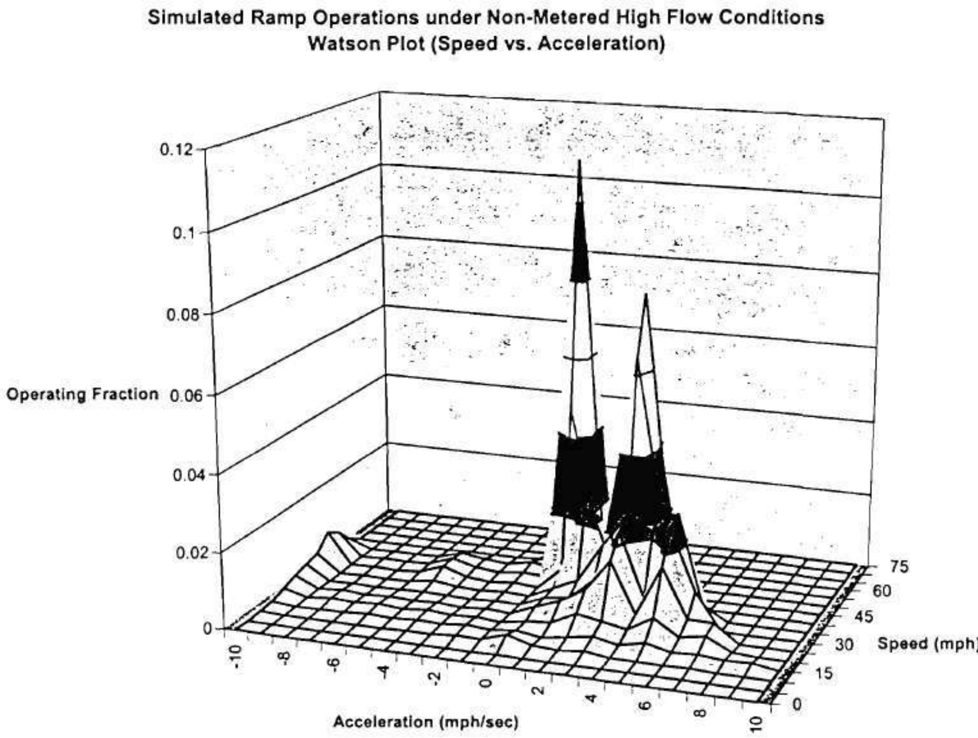


Figure 6-16

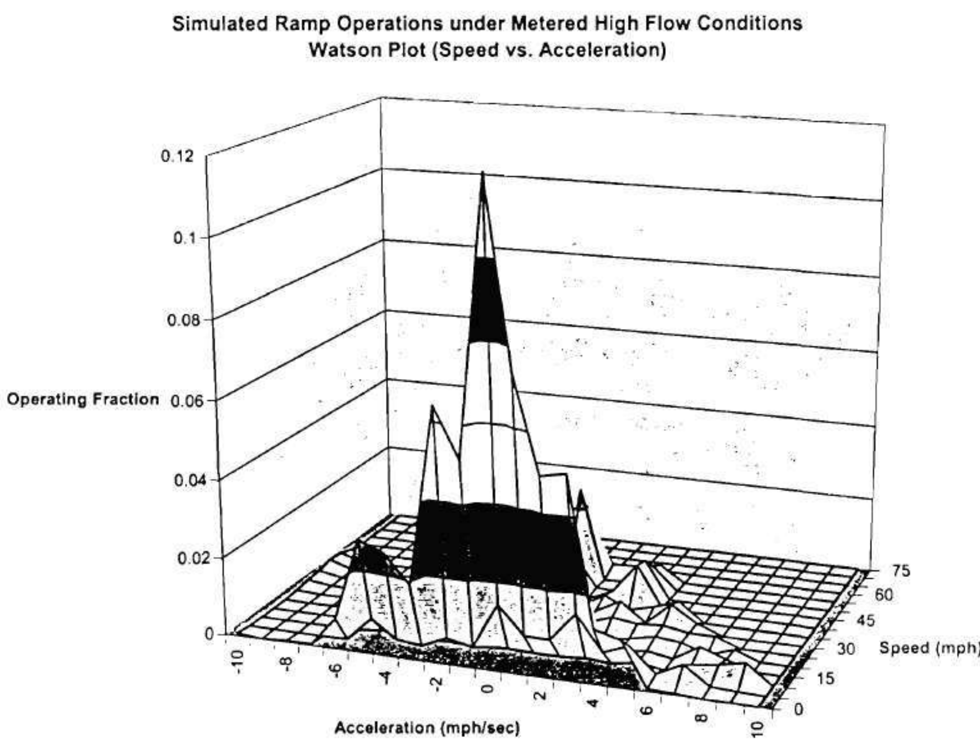


Figure 6-17

Simulated I75 Operations under Non-Metered High Flow Conditions
Watson Plot (Speed vs. Acceleration)

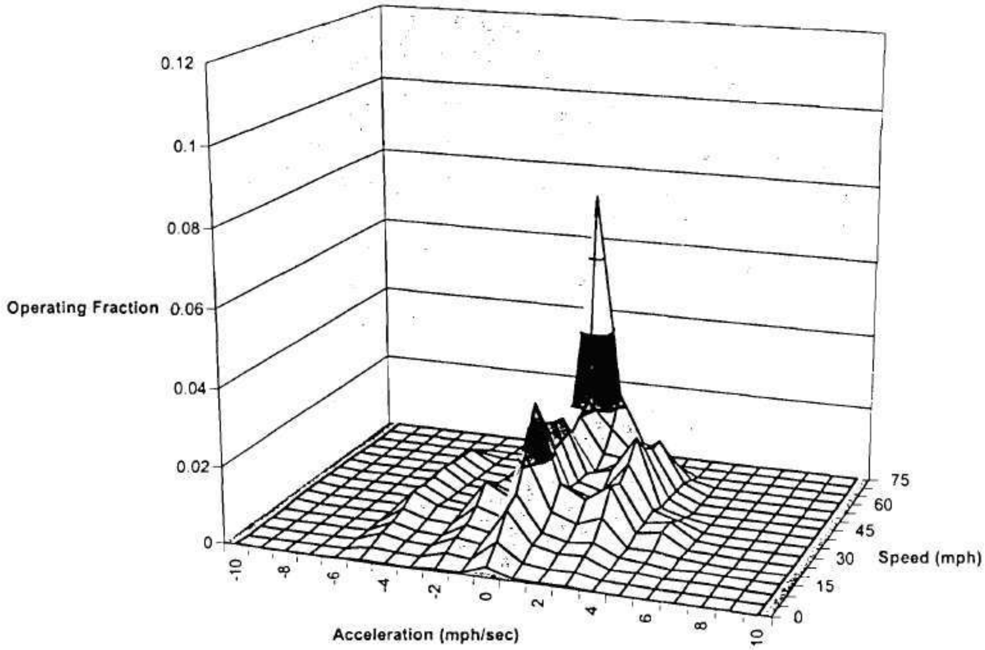


Figure 6-18

Simulated I75 Operations under Metered High Flow Conditions
Watson Plot (Speed vs. Acceleration)

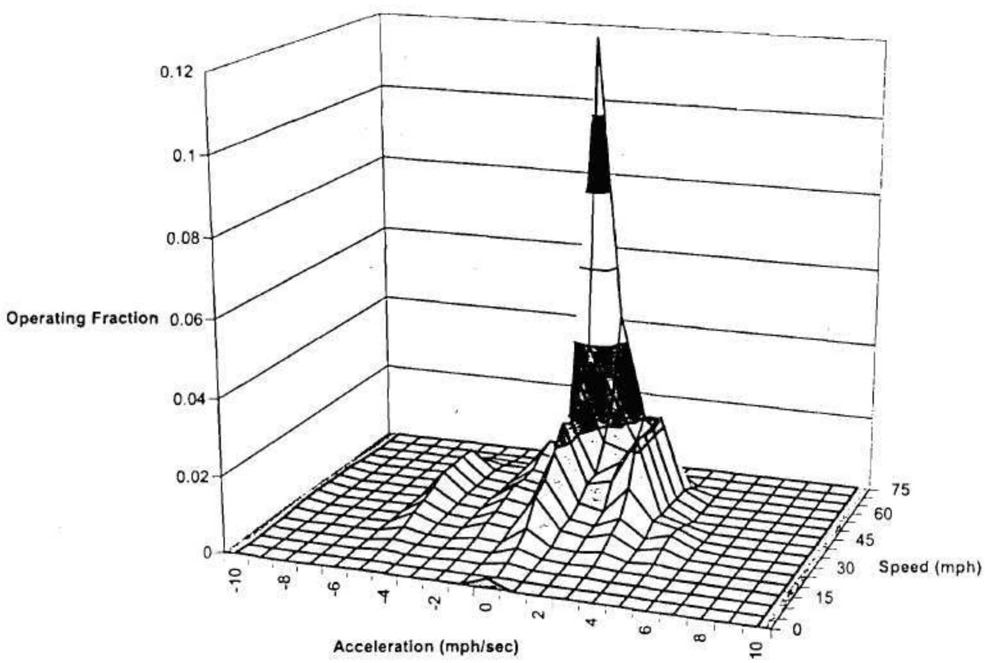


Figure 6-19

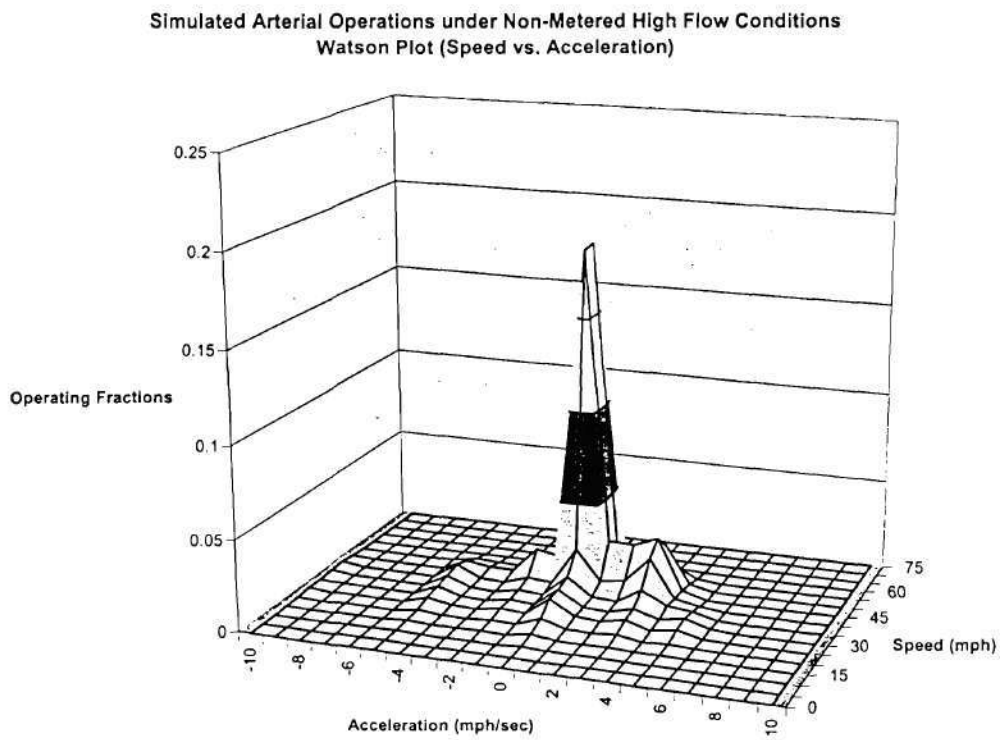
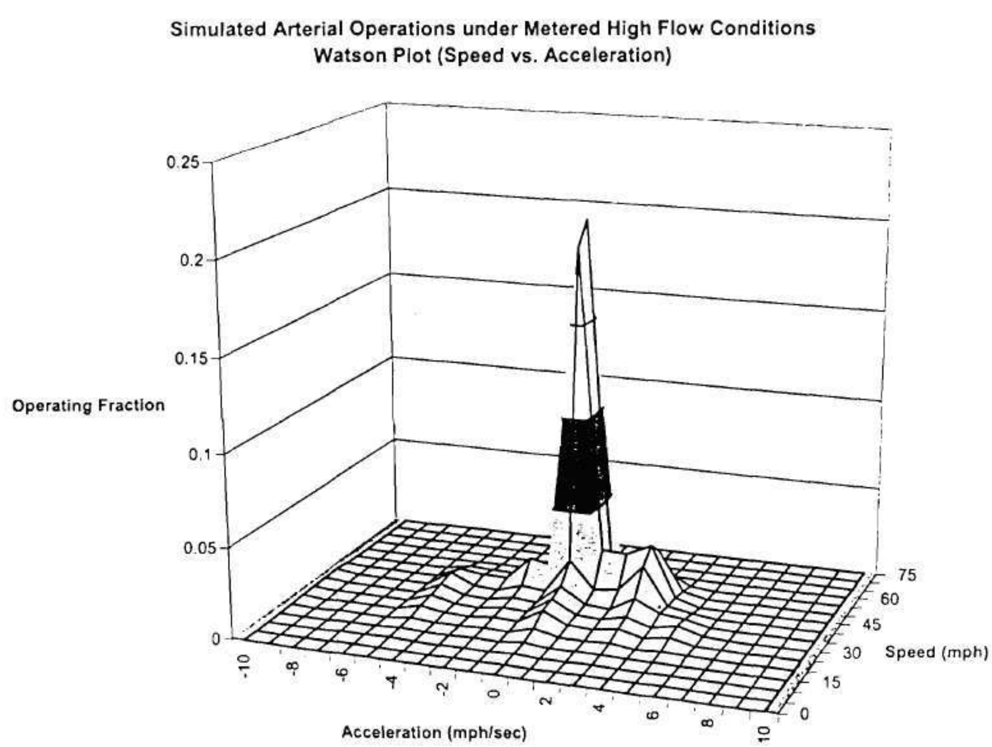


Figure 6-20



The Watson plots for simulation-derived speed and acceleration profiles were used to develop the MEASURE emissions rates for the observed vehicle fleets on the corridor using the same procedures outlined in Chapter 5. Table 6-4 contains the emission rates for the mainline freeways, ramps, and arterials for the observed and high flow scenarios.

Table 6-4
Predicted MEASURE Emissions Rates
for CORSIM Simulation Runs

	Non-metered Observed Mainline	Non-metered Observed Ramps	Non-metered Observed Arterials
Mean CO gram/sec	0.03688	0.05118	0.0385
Mean NOx gram/sec	0.02583	0.02888	0.0331
Mean HC gram/sec	0.03637	0.03060	0.0404
	Metered Observed Mainline	Metered Observed Ramps	Metered Observed Arterials
Mean CO gram/sec	0.03675	0.02919	0.0394
Mean NOx gram/sec	0.02628	0.00666	0.0389
Mean HC gram/sec	0.03701	0.00889	0.0472
	Non-Metered High Flow Mainline	Non-Metered High Flow Ramps	Non-Metered High Flow Arterials
Mean CO gram/sec	0.03744	0.05095	0.0365
Mean NOx gram/sec	0.02345	0.02898	0.0243
Mean HC gram/sec	0.03285	0.03074	0.0308
	Metered High Flow Mainline	Metered High Flow Ramps	Metered High Flow Arterials
Mean CO gram/sec	0.03743	0.02944	0.03938
Mean NOx gram/sec	0.02412	0.00730	0.03665
Mean HC gram/sec	0.03379	0.00930	0.04450

The CORSIM modeling results presented in this Chapter include the following standard metrics: vehicle-miles traveled, vehicle-hours of movement, and vehicle-hours delay. CORSIM outputs also provided average speeds. The simulation outputs do not include a metric for total number of trips. This is because the project has numerous entry and exit points so one trip may be 0.5 miles while another trip may be 1.5 miles. Similarly, one trip may be on arterial roads only while another may be on freeways. The simulated traffic volumes can represent vehicles that never actually enter the freeway (that is, they pass through the system on an arterial route). With arterial queuing, many vehicles destined for the system never actually enter the freeway during the simulation period. Hence, simulation programs steer away from this "trip" measure of effectiveness (MOE) and provide vehicle miles and hours of travel information broken down for arterial roads (NETSIM), and freeway mainlines and ramps (FRESIM). As such, comparisons of the two scenarios are difficult.

As mentioned above, the simulation runs for metered and non-metered conditions do not necessarily include the same number of vehicle trips. The goal of the simulation modeling is to determine whether mass emissions under a metered scenario differ significantly from emissions under a non-metered scenario. However, if the number of vehicles in each simulation differed significantly, the emissions results would differ not only due to the conditions under which the vehicles operate but also due to the number of vehicle trips modeled. Table 6-1 indicates that simulation scenario VMT estimates differ by as much as 15% for arterials, 3% for mainline freeways, and 20% for ramps. Because the vehicle miles of travel on these three functional classes differ significantly between scenarios, it is clear that a different number of vehicles are being modeled in these scenarios.

Because the roadway link lengths remain constant across in each modeled scenario, vehicle miles of travel per functional class (arterials, mainlines, and ramps) are approximately correlated with number of trips (or number of vehicles crossing the system in each scenario). To account for the difference in vehicle trips simulated between scenarios, the research team adjusted the vehicle hours of travel across scenarios to reflect the noted difference in vehicle miles of travel. Hence, if the meters-on scenario simulation resulted in 97% of the VMT of the meters-off scenario simulation, the vehicle hours of travel for the meters-off scenario were adjusted downward to reflect the presumed difference in number of vehicles simulated. Travel hours were adjusted before estimating emissions.

The mass emissions for each of the scenarios were estimated by multiplying simulation-derived and then volume-adjusted total hours of vehicle activity (converted to seconds) by the applicable gram/second emission rates in Table 6-4. Tables 6-5 and 6-6 contain the adjusted vehicle hours of travel figures used in estimating mass emissions. Table 6-5 presents the predicted mass emissions by pollutant for the observed flows with and without ramp metering. Table 6-6 presents the predicted emissions by pollutant for the observed and high flow scenarios with and without ramp metering. The last column in each of the tables indicates the percentage change in emissions resulting from the implementation of ramp metering for each scenario.

Table 6-5
Predicted Change in Emissions by Pollutant
Volume-Adjusted CORSIM Simulation Runs
Observed Traffic Flows with and without Meters in Operation

Adjusted Vehicle Hours		**Observed Flow Non-Metered**	**Observed Flow Metered**	**Simulated Impact of Ramp Metering**
	NETSIM Total	276	1,049	280.1%
	Mainline Total	2,072	1,890	-8.8%
	Ramp Total	24	125	419.9%
	Total	2,373	3,064	29.1%
Ramps and Mainlines Only				
CO grams	Mainline Total	287,244	268,078	-6.7%
CO grams	Ramp Total	4,430	13,136	196.5%
	Total	291,674	281,213	-3.6%
NOx grams	Mainline Total	246,956	264,676	7.2%
NOx grams	Ramp Total	2,500	2,997	19.9%
	Total	249,455	267,673	7.3%
HC grams	Mainline Total	301,420	321,149	6.5%
HC grams	Ramp Total	2,648	4,001	51.1%
	Total	304,069	325,149	6.9%
System Totals				
CO grams	NETSIM Total	36,643	138,783	278.7%
CO grams	Mainline Total	287,244	268,078	-6.7%
CO grams	Ramp Total	4,430	13,136	196.5%
	Total	328,317	419,996	27.9%
NOx grams	NETSIM Total	25,664	99,244	286.7%
NOx grams	Mainline Total	246,956	264,676	7.2%
NOx grams	Ramp Total	2,500	2,997	19.9%
	Total	275,119	366,916	33.4%
HC grams	NETSIM Total	36,136	139,765	286.8%
HC grams	Mainline Total	301,420	321,149	6.5%
HC grams	Ramp Total	2,648	4,001	51.1%
	Total	340,204	464,914	36.7%

Table 6-6
Predicted Change in Emissions by Pollutant
Volume-Adjusted CORSIM Simulation Runs
Theoretical High Volume Flows with and without Meters in Operation

		High Flow Non-Metered	High Flow Metered	Simulated Impact of Ramp Metering
Adjusted Vehicle Hours				
	NETSIM Total	283	1,055	273.2%
	Mainline Total	2,713	2,095	-22.8%
	Ramp Total	24	126	419.4%
	Total	3,020	3,276	8.5%
Ramps and Mainlines Only				
CO grams	Mainline Total	356,513	297,004	-16.7%
CO grams	Ramp Total	4,449	13,354	200.1%
	Total	360,962	310,358	-14.0%
NOx grams	Mainline Total	229,047	276,414	20.7%
NOx grams	Ramp Total	2,531	3,311	30.8%
	Total	231,578	279,726	20.8%
HC grams	Mainline Total	300,838	335,619	11.6%
HC grams	Ramp Total	2,684	4,218	57.1%
	Total	303,523	339,837	12.0%
System Totals				
CO grams	NETSIM Total	38,104	142,159	273.1%
CO grams	Mainline Total	356,513	297,004	-16.7%
CO grams	Ramp Total	4,449	13,354	200.1%
	Total	399,066	452,517	13.4%
NOx grams	NETSIM Total	24,731	91,608	270.4%
NOx grams	Mainline Total	229,047	276,414	20.7%
NOx grams	Ramp Total	2,531	3,311	30.8%
	Total	256,309	371,333	44.9%
HC grams	NETSIM Total	33,433	128,334	283.9%
HC grams	Mainline Total	300,838	335,619	11.6%
HC grams	Ramp Total	2,684	4,218	57.1%
	Total	336,955	468,172	38.9%

6.4.1 Observed Flow Results

Simulation results differed significantly from observed traffic flow results for the observed metered and non-metered scenarios. The differences between observed and simulated average speed conditions were most pronounced for activity on the metered and non-metered ramps. In the simulation, ramp speeds were predicted to drop from 44 mph to 8 mph under metered conditions. However, observed ramp speeds only dropped from 41 mph to 32 mph. A large percentage of activity occurs in long deceleration and acceleration zones, while only a short period of time occurs in slowing and stopping activity at the ramp meter stop line (for an example, see Figure 5-6). Acceleration distributions also differed significantly as illustrated in the Watson plots. The emissions predictions from field data indicated between a 30 and 46% increase in ramp HC emissions and between a 2% to 22% decrease in ramp NOx emissions, depending on the onramp in question (Table 5-17). The simulation runs predicted a net increase in ramp HC emissions of 50%.

The emissions predictions from field data indicated between a 2% to 22% decrease in ramp NOx emissions, depending on the onramp in question (Table 5-17). Whereas, the simulation runs predicted a net increase in NOx ramp emissions of 21%. The simulation results indicate an 80% reduction in NOx emissions rates, but a 400% increase in link travel time, resulting in the projected emissions increase. The projected increase in ramp travel time was never noted during the field observations, resulting in the significant difference between simulated and observed results. Hence, the simulation model does not provide accurate estimates of change in modal activity or emissions. Given the field findings, simulation model performance for ramps requires significant improvement.

The research team does not believe that the noted differences between observed and simulated ramp activity is the result of model calibration problems. The differences appear to result inherently from the CORSIM model algorithms at the interface nodes between the NETSIM (arterial modeling) and FRESIM (freeway simulation) components. A smooth transfer of vehicles is not ensured across this interface under congested conditions. The ramp metering results indicate that additional research should be performed to improve the performance of CORSIM at the interface nodes. The ramp metering data, and data from similar field studies, could be used to calibrate or replace the CORSIM interface routines.

The simulation model also predicted significantly lower average freeway speeds, and significantly greater changes in average freeway speeds for metering, than were observed in the field. Ramp meter simulations predicted an increase in average freeway speeds from 52 mph to 55 mph. In the field, observed non-metered freeway speeds (from laser gun and floating car runs) started at 62 mph and only increased to 63 mph under metered conditions.

The research team spent a great deal of time testing a variety of calibration approaches to improve the CORSIM model performance for freeflow freeway speeds. For example, the team increased maximum freeflow speeds well above the standard for urban environments. An additional factor appears to be CORSIM upstream limitations. In most simulations, entry link lengths must be adjusted to avoid simulation spillback (losing cars out of the modeled system) at the model boundaries. The research team had to artificially extend entry link lengths well beyond the original study area to avoid spillback errors. Additional vehicles introduced upstream of Northside ramp may have resulted in an overall decrease in simulated average speeds, because these vehicles encounter flow restriction at the Northside off-ramp (i.e., before entering the actual study area). Hence, some speed prediction errors may be systemic, in that the simulated speed reductions occur in areas not monitored by the field team. However, the research team believes that a good portion of the speed prediction problem results directly from problems with the CORSIM lane changing and car following routines for HOV lanes and multi-lane environments. These routines may not accurately reflect the operations on Atlanta infrastructure or Atlanta's driver behavior. A combination of many factors that cannot be mitigated through simple calibration changes appears to have contributed to the speed prediction differences.

The significant difference in simulated average speeds under metered and non-metered conditions for mainline freeways is of great concern in emissions modeling. Emissions predictions under both the MEASURE Aggregate Modal Model and MOBILE5b are affected. Average speed is a variable in both models, and load surrogates in MEASURE are also impacted by CORSIM-predicted speed/acceleration combinations. Similarly, the much larger difference in simulated changes in average speeds provides a significant difference in predicted emission rate changes between simulated and observed conditions.

Chapter 5 indicated that field observations yielded an estimated 2% decrease in mainline freeway HC emissions and an estimated 4% increase in mainline freeway NOx emissions. However, simulation results predicted a much larger increase in both HC and NOx mainline freeway emissions. Simulations indicated that a nearly 7% increase would result in both HC and NOx emissions for the freeway mainlines. Field observations recorded higher speed activity and more hard acceleration conditions under all ranges of speeds that lead to higher emissions in the MEASURE modeling regime. The difference between emissions estimates arise predominantly from the difference in predicted starting points and changes in average speeds, and to some extent from differences in percentage of operations under higher power demand conditions (inertial power surrogate values). The simulation model poorly predicts the high-speed activity that results on the freeway for this case study under current traffic conditions. Again, further research on appropriate calibration of the FRESIM routines for this study corridor is warranted.

Tables 6-5 and 6-6 provide estimates for ramps and mainlines, for comparison with field-collected vehicle operating condition data (arterial operating data were not collected as a part of this study, so arterials emissions could not be predicted from field observations). The tables also provide results for ramps, mainlines and arterials taken together as a simulated system. The arterial emissions are significant. In most of the simulations, arterial emissions comprise approximately 10% of the systems emissions for the non-metered system. Under metered conditions, the arterial emissions are predicted to increase by approximately 300%, significantly contributing to the total predicted emissions increases from the simulated system (raising the contribution of arterials to more than 25% of system emissions). When arterial activity is factored into the emissions, ramp metering for the simulation is predicted to increase system-wide NOx and HC emissions by more than 30% (instead of only 7% when arterials are omitted).

6.4.2 High Flow Results

The simulation exercise of maximizing the freeway entry volumes into the modeled corridor illustrates the potential impact of ramp metering on traffic flows and emissions as the flow volumes approach (but never achieve) breakdown conditions. The high flow simulation exercises corroborate independent research efforts that have historically demonstrated that ramp metering has a potentially significant impact on mainline average freeway speeds under heavy flow conditions (roughly 10mph in this case). With ramp metering, mainline freeway hours of vehicle activity dropped by nearly 20% under simulated high flow conditions, compared to a drop of only 8% under observed flow conditions. This occurred while ramp delay and arterial congestion contributions remained constant. Hence, as expected, ramp metering provides greater mainline freeway time savings under heavier traffic flow conditions. The basic problem is that under metered conditions gram/second emission rates increased at a greater rate than the rate of travel times decline. Thus, high volume conditions lead to potentially higher mass emissions for the metered scenarios than observed flow conditions. In this case, the net emissions increase from metering rose from 33% to 45% for NOx and from 37% to 39% for HC when moving to higher flow conditions. Hence, emissions impacts were even worse under high flow conditions than under observed conditions.

There are no field observations under high flow conditions to which researchers can compare these estimates. However, the differences between simulated and observed traffic data under normal operating conditions indicate that simulated flows for high flow conditions are also likely to underestimate the maximum speeds and acceleration rates on the mainline. Hence, emissions under real world metered conditions are also likely to be greater than predicted by the simulation routines.

Even under the modeled high flow conditions, traffic conditions on the study section are incapable of achieving complete flow breakdown in the absence of an incident. Because the research team also desired to examine the potential benefits of ramp metering on emissions that result from severe congestion, the researchers simulated an additional scenario set for a lane closure in peak-hour conditions.

6.5 Lane Closure Simulations for Observed and High Flows

To examine the potential effects of metering under the onset of severe traffic congestion, a set of four lane closure simulations were performed for a peak-hour (5:00 p.m. until 6:00 p.m.) observed traffic flow condition. The research team first simulated metered and non-metered conditions for traffic flows similar to those observed in the field at peak-hour traffic volumes. An incident was simulated at 5:05 p.m. in the region of the Peachtree Battle overpass for the northbound direction of travel. The incident results in queued traffic conditions across the ramp terminals at the Howell Mill Road and Northside Drive onramps. The research team simulated both metered and non-metered conditions for the peak hour with and without the incident at observed flow conditions. The simulated incident was cleared and by the end of the one-hour period, and traffic conditions returned to normal. This analysis provided the opportunity to evaluate the effect of ramp metering under observed and then heavily congested and "clearing" conditions. Table 6-7 contains the measures of effectiveness for the peak-hour simulations.

Table 6-7
Summary Measures of Effectiveness for Metered and Non-Metered Conditions
Simulations of Observed Flows with and without Lane Closure

Table Values Represent the Average Estimate based on 30 CORSIM Simulation Runs	**Peak-Hour No Incident Non-Metered Observed Flow**	**Peak-Hour No Incident Metered Observed Flow**	**Peak-Hour Incident Non-Metered Observed Flow**	**Peak-Hour Incident Metered Observed Flow**
Vehicle-Miles Traveled:				
Total Corridor	37,780	35,746	37,611	35,726
NETSIM Total	1,653	1,361	1,648	1,362
FRESIM Total	36,127	34,385	35,962	34,364
Mainline Total	35,663	34,031	35,500	34,010
Ramp Total	464	354	463	354
Vehicle-Hours Move Time:				
Total Corridor	569	538	569	539
NETSIM Total	54	44	54	44
FRESIM Total	515	493	515	495
Mainline Total	508	484	508	485
Ramp Total	7	9	7	9
Vehicle-Hours Delay Time:				
Total Corridor	235	432	472	587
NETSIM Total	59	272	59	273
FRESIM Total	176	160	413	313
Mainline Total	172	126	410	279
Ramp Total	4	34	4	34
Vehicle-Hours of Activity:				
Total Corridor	804	970	1,041	1,126
NETSIM Total	113	316	113	317
FRESIM Total	691	653	928	808
Mainline Total	680	610	918	764
Ramp Total	11	43	11	43

Average speed and speed distributions serve as additional measures of effectiveness for changes in operating conditions. Table 6-8 presents the means and standard deviations of speeds under metered versus non-metered observed flow conditions for the peak-hour simulations. Figure 6-21 graphically represents the speed distributions for ramps and freeways under simulated metered versus non-metered observed flows conditions without a lane closure. Table 6-9 and Figure 6-22 provide similar information for peak-hour lane closure (congested and clearing) conditions. Figures 6-23 to 6-34 illustrate the speed/acceleration operating profiles predicted by the simulation model for each modeled scenario.

Table 6-8
Peak-Hour Speed Comparison for Metered and Non-Metered Peak-Hour Simulation Analyses (Observed Flows)

Runs = 30	Ramp Speeds		Freeway Speeds	
	Meter On	Meter Off	Meter On	Meter Off
Mean (mph)	8.1	43.5	55.8	52.4
Std. Dev. (mph)	0.11	0.20	0.71	1.05

Figure 6-21
Peak-Hour Speed Comparison of Metered and Non-Metered Peak-Hour Simulation Analyses (Observed Flows)

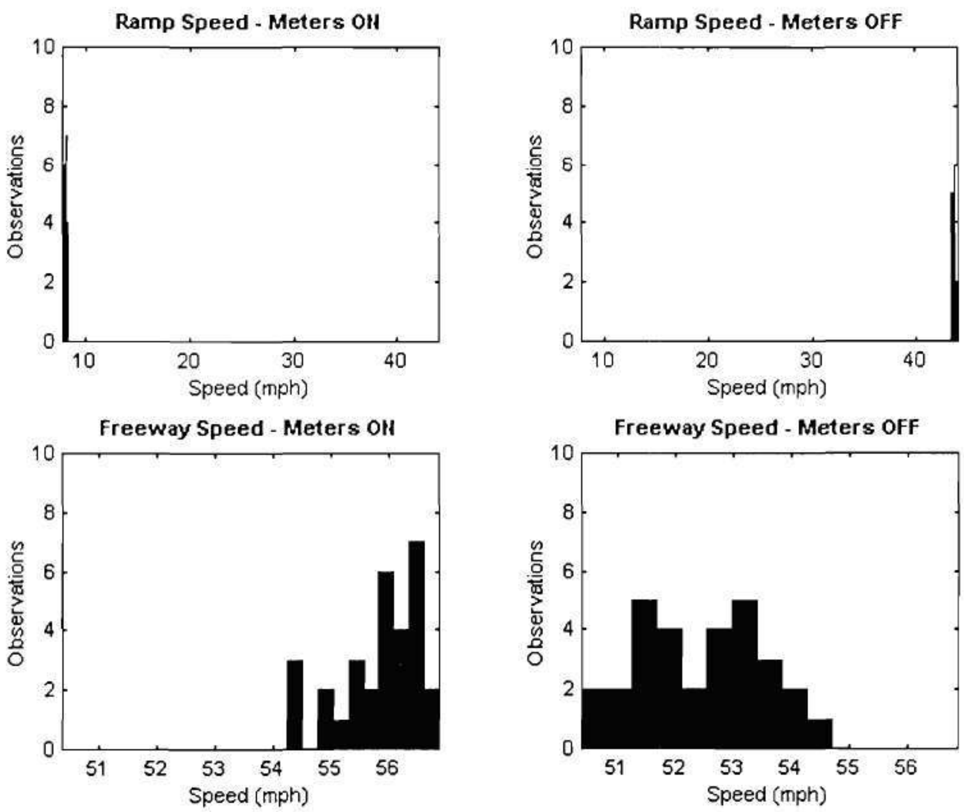


Table 6-9
Peak-Hour Speed Comparison for Metered and Non-Metered Peak-Hour Lane Closure Simulation Analyses

Runs = 30	Ramp Speeds		Freeway Speeds	
	Meter On	Meter Off	Meter On	Meter Off
Mean (mph)	8.1	42.9	44.5	38.7
Std. Dev. (mph)	0.11	0.59	1.08	1.35

Figure 6-22
Peak-Hour Speed Comparison of Meter and Non-Metered Peak-Hour Lane Closure Simulation Analyses

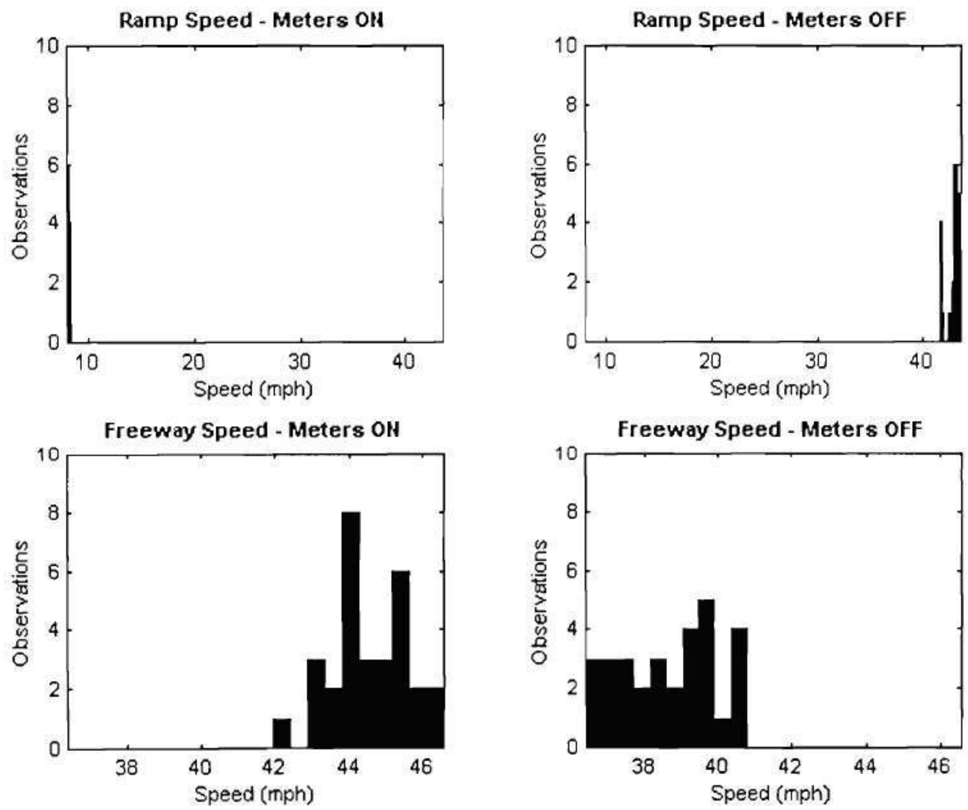


Figure 6-23

Simulated Ramp Operations under Non-Metered Peak Hour Non-Incident Conditions
Watson Plot (Speed vs. Acceleration)

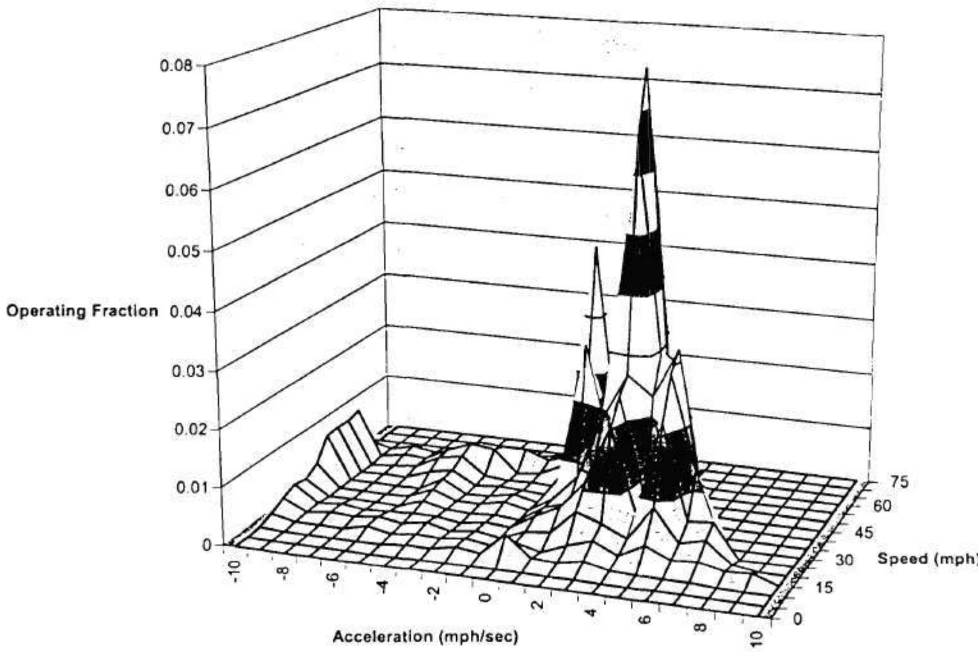


Figure 6-24

Simulated Ramp Operations under Metered Peak Hour Non-Incident Conditions
Watson Plot (Speed vs. Acceleration)

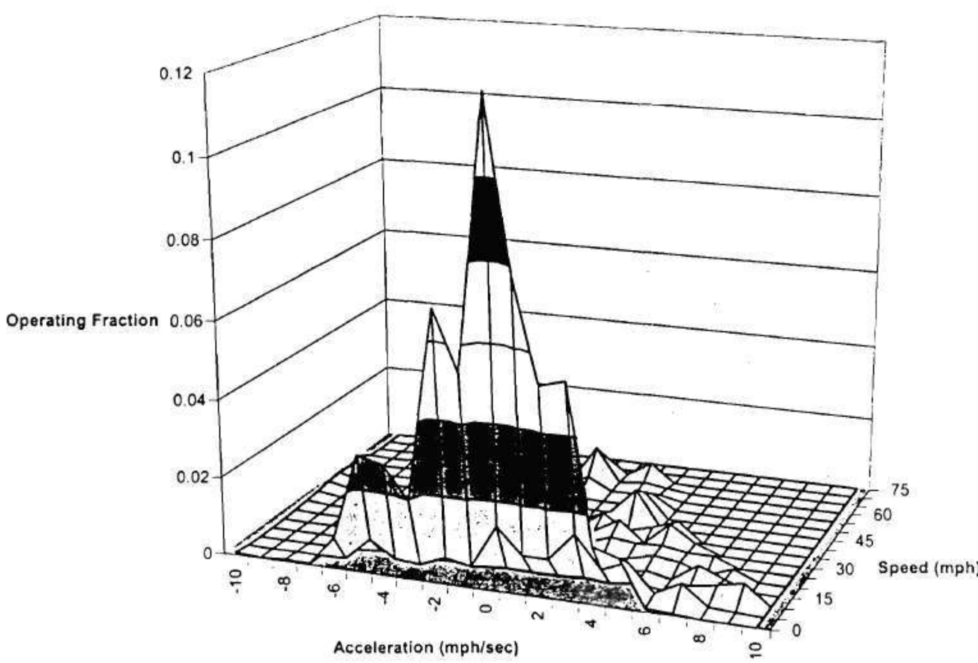


Figure 6-25

Simulated I75 Operations under Non-Metered Peak Hour Non-Incident Conditions
Watson Plot (Speed vs. Acceleration)

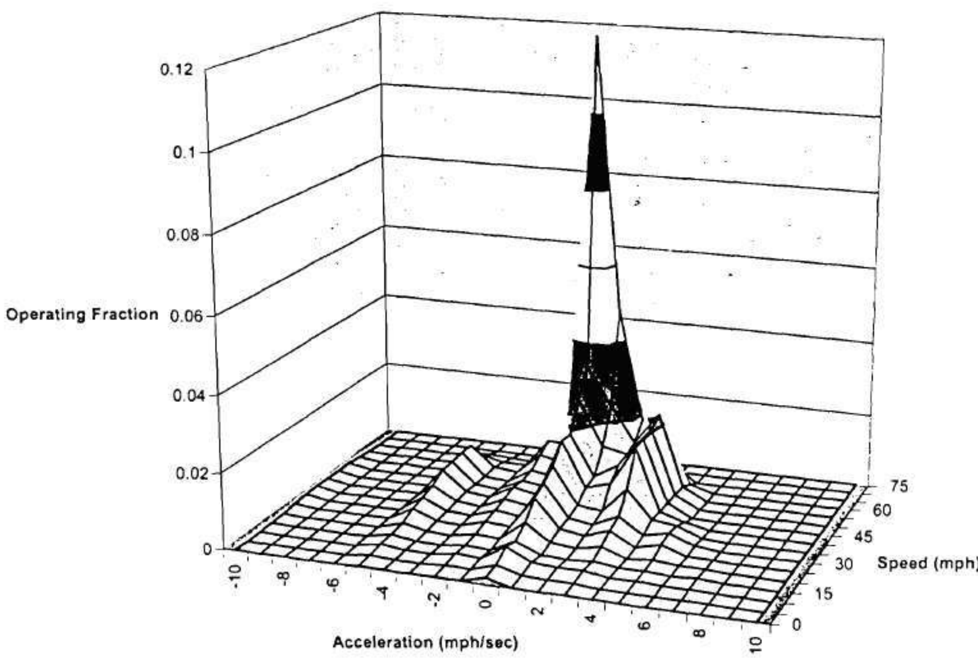


Figure 6-26

Simulated I75 Operations under Metered Peak Hour Non-Incident Conditions
Watson Plot (Speed vs. Acceleration)

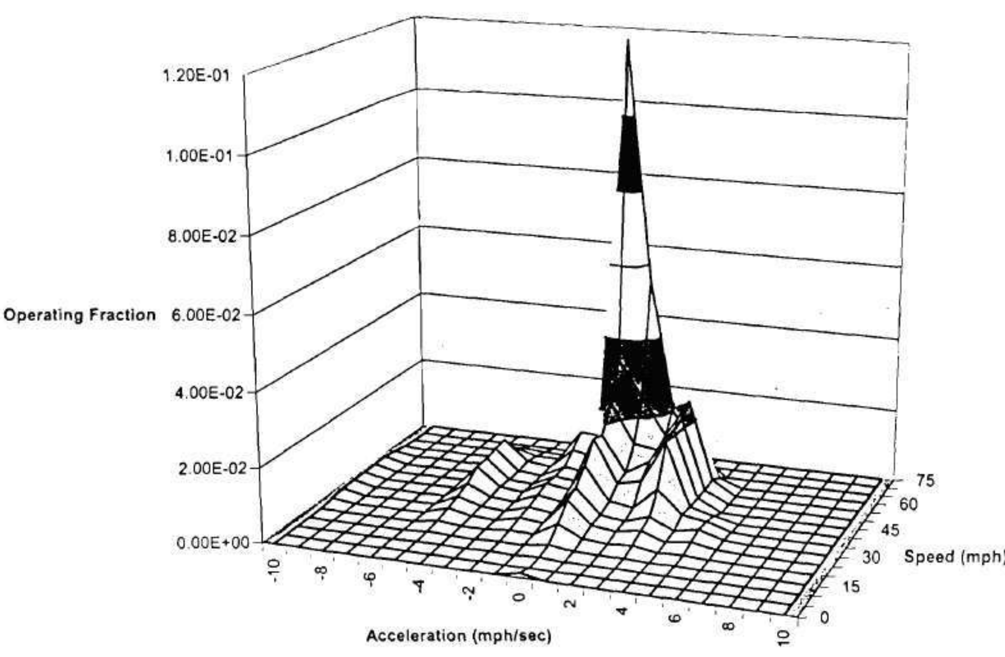


Figure 6-27

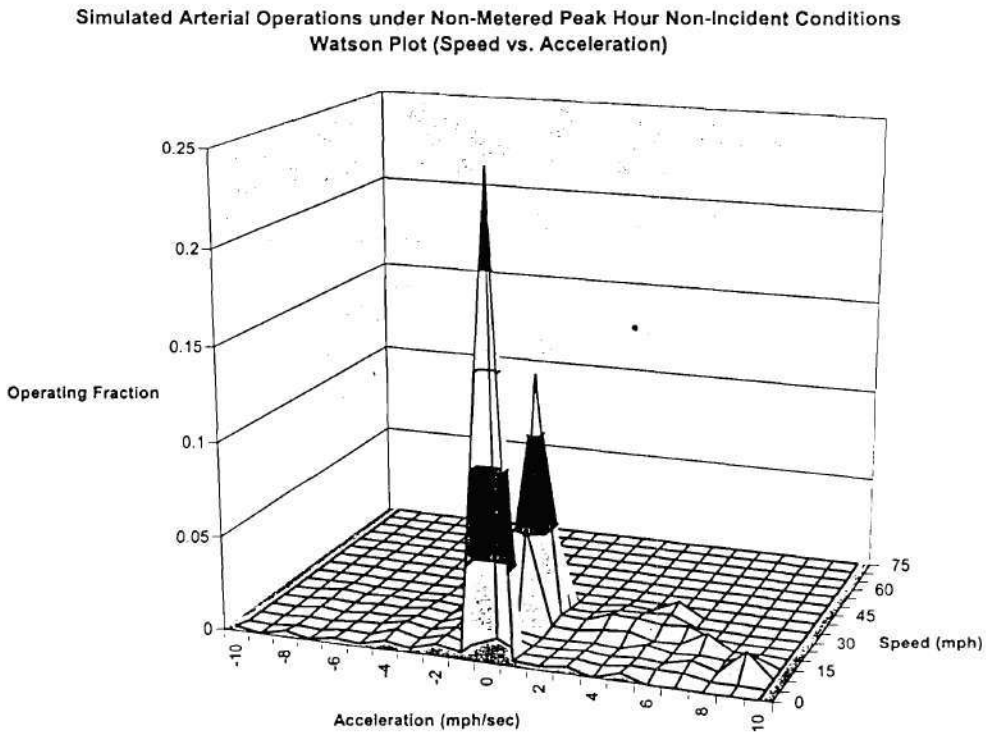


Figure 6-28

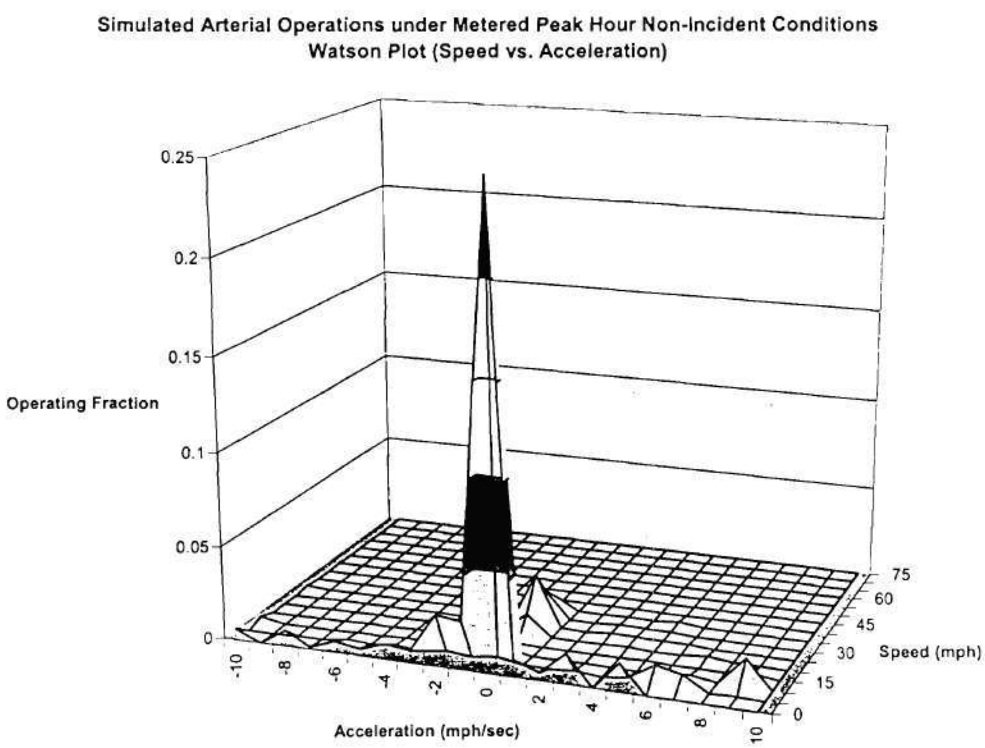


Figure 6-29

Simulated Ramp Operations under Non-Metered Peak Hour Incident Conditions
Watson Plot (Speed vs. Acceleration)

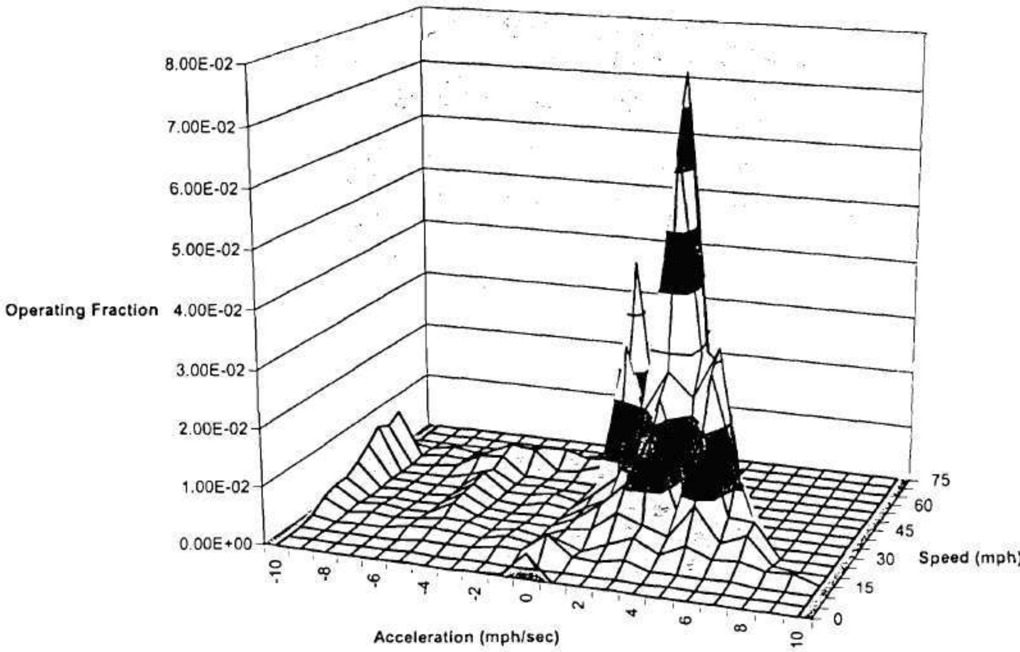


Figure 6-30

Simulated Ramp Operations under Metered Peak Hour Incident Conditions
Watson Plot (Speed vs. Acceleration)

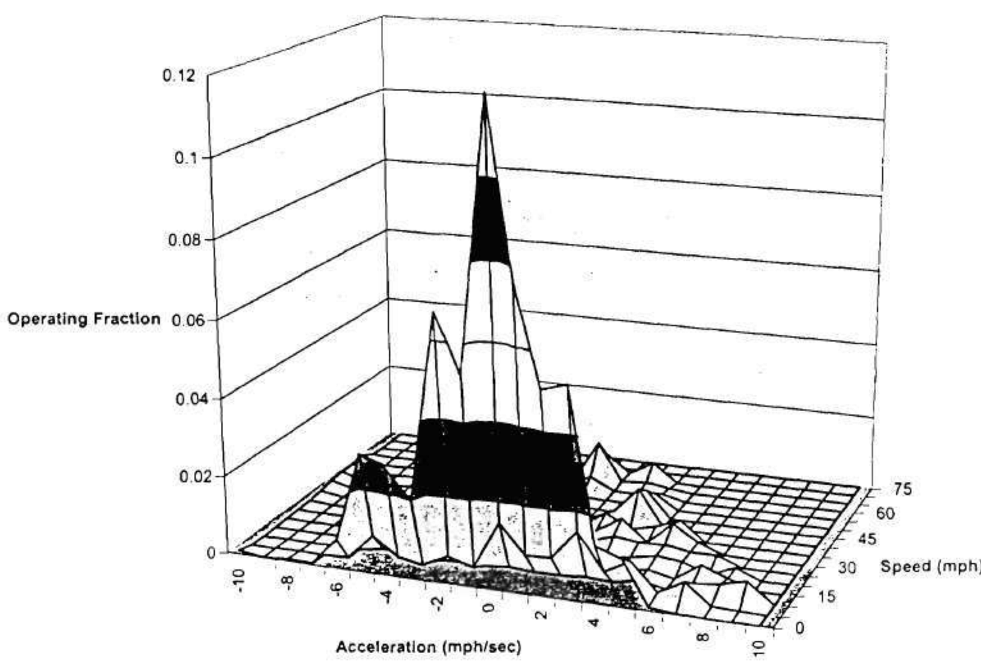


Figure 6-31

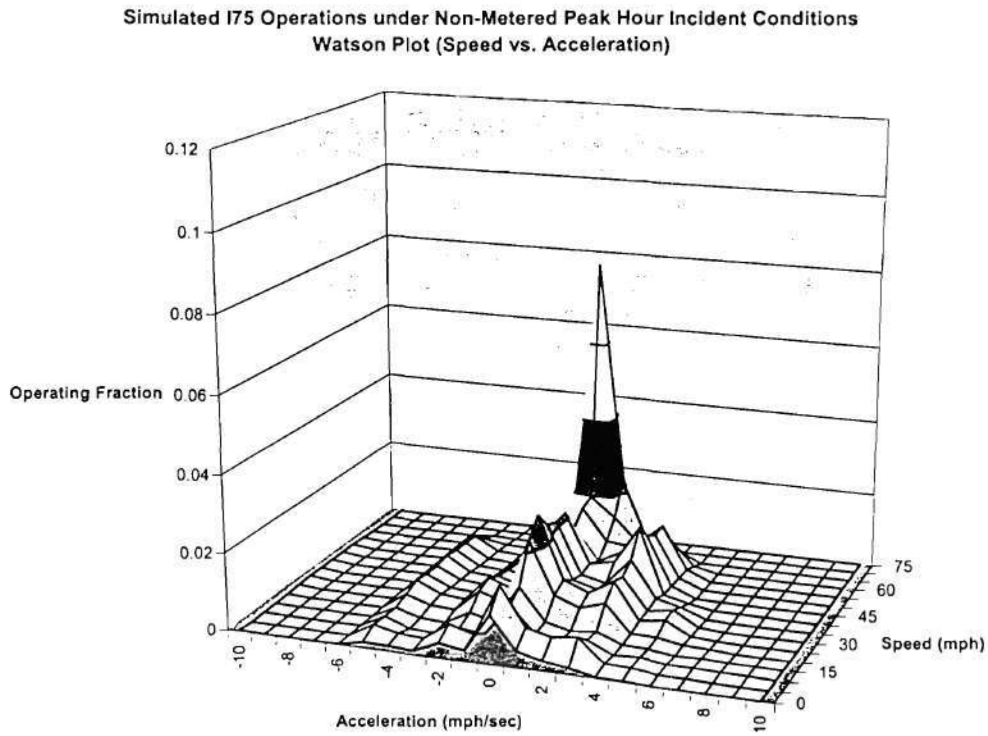


Figure 6-32

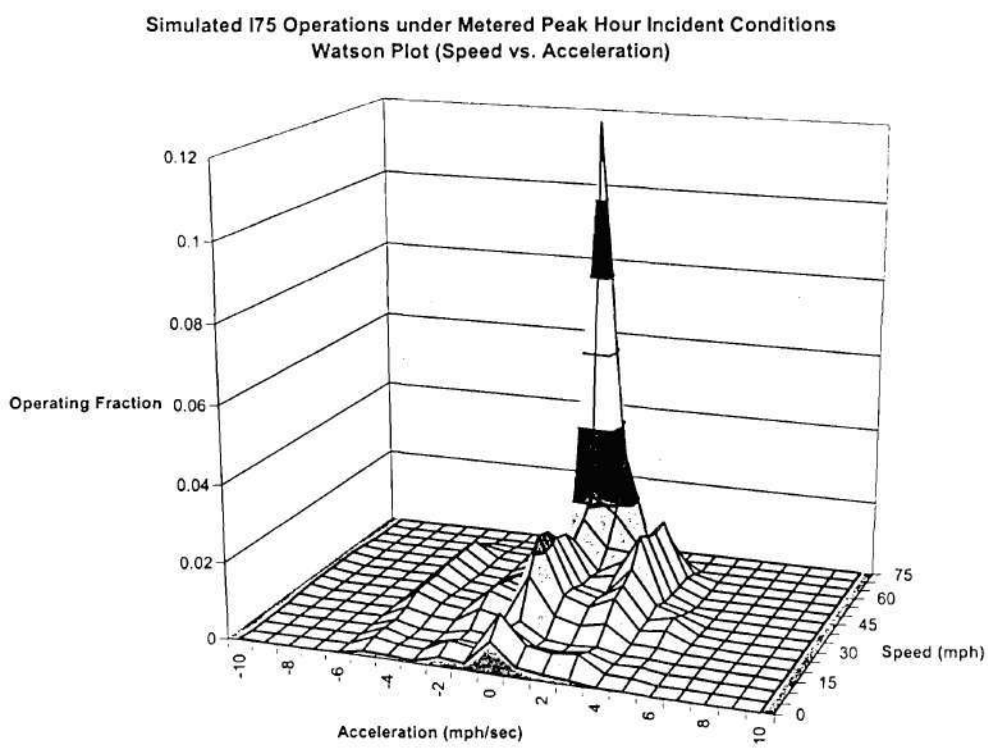


Figure 6-33

Simulated Arterial Operations under Non-Metered Peak Hour Incident Conditions
Watson Plot (Speed vs. Acceleration)

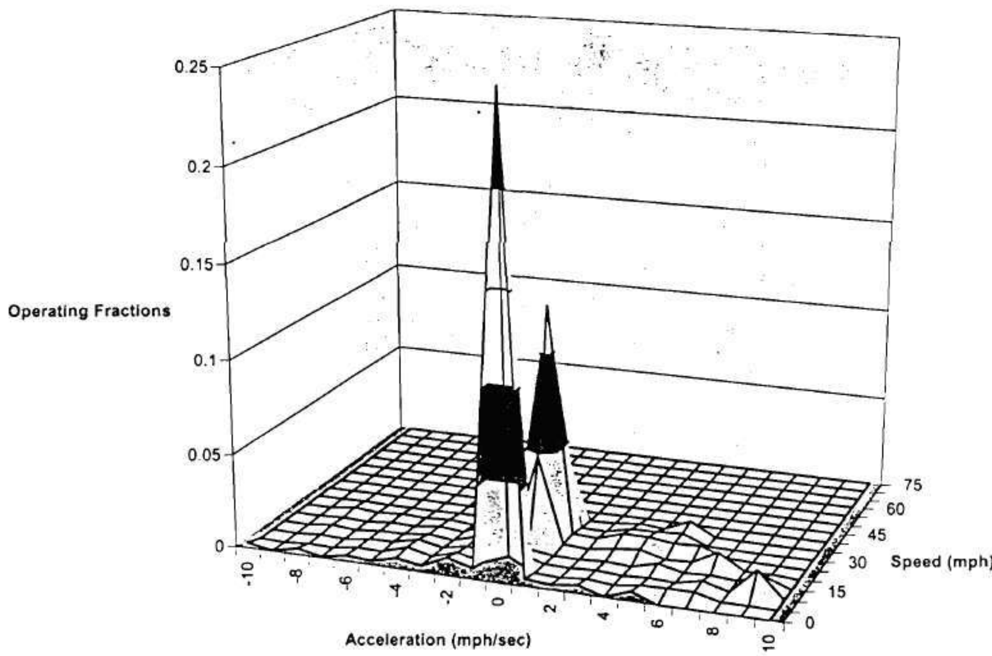
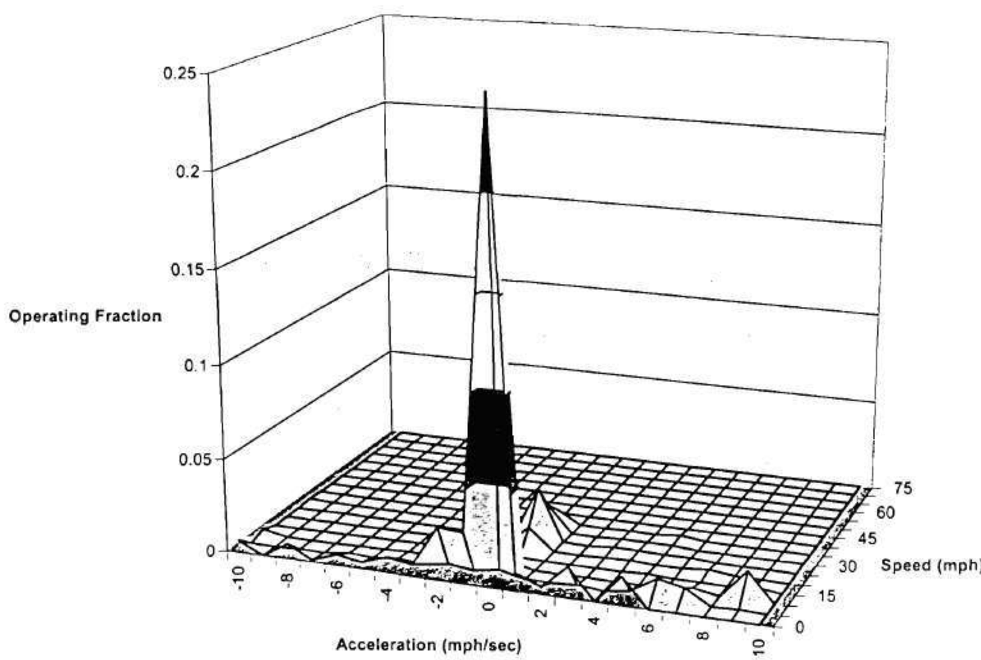


Figure 6-34

Simulated Arterial Operations under Metered Peak Hour Incident Conditions
Watson Plot (Speed vs. Acceleration)



The Watson plots for simulation-derived speed and acceleration profiles were used to develop the MEASURE emissions rates for the observed vehicle fleets on the corridor using the same procedures outlined in earlier Chapters. Table 6-10 contains the emission rates for freeway mainlines, ramps, and arterials for the peak-hour observed flow and lane closure scenarios.

Table 6-10
Predicted MEASURE Emissions Rates
for CORSIM Peak-Hour Observed and Lane Closure Simulation Runs

	Non-metered Peak-Hour Observed Mainline	Non-metered Peak-Hour Observed Ramps	Non-metered Peak-Hour Observed Arterials
Mean CO gram/sec	0.03907	0.05474	0.02904
Mean NOx gram/sec	0.03714	0.03670	0.00686
Mean HC gram/sec	0.04508	0.03411	0.00956

	Metered Peak-Hour Observed Mainline	Metered Peak-Hour Observed Ramps	Metered Peak-Hour Observed Arterials
Mean CO gram/sec	0.03961	0.02894	0.02581
Mean NOx gram/sec	0.04120	0.00756	0.00347
Mean HC gram/sec	0.04973	0.00921	0.00580

	Non-Metered Peak-Hour Incident Mainline	Non-Metered Peak-Hour Incident Ramps	Non-Metered Peak-Hour Incident Arterials
Mean CO gram/sec	0.03579	0.05423	0.02879
Mean NOx gram/sec	0.02387	0.03583	0.00660
Mean HC gram/sec	0.03032	0.03326	0.00923

	Metered Peak-Hour Incident Mainline	Metered Peak-Hour Incident Ramps	Metered Peak-Hour Incident Arterials
Mean CO gram/sec	0.03707	0.02902	0.02580
Mean NOx gram/sec	0.02924	0.00764	0.00345
Mean HC gram/sec	0.03634	0.00932	0.00578

The goal of the simulation modeling is to determine whether emissions under a metered scenario differ significantly from emissions under a non-metered scenario. However, as discussed in the last section, simulation runs for metered and non-metered conditions do not necessarily include the same number of vehicle trips. Table 6-7 indicates that simulation scenario VMT estimates differ by as much as 18% for arterials, 5% for mainline freeways, and 24% for ramps. To account for the difference in vehicle trips simulated between scenarios, the vehicle hours of travel across scenarios were adjusted to reflect the noted difference in vehicle miles of travel. Hence, if the Scenario 1 meters-on simulation resulted in 97% of the VMT of the Scenario 2 meters-off simulation, the vehicle hours of travel for scenario 2 were adjusted downward to reflect the presumed difference in number of vehicles simulated. This volume adjustment was performed before using travel hours to estimate emissions.

The mass emissions estimate for each scenario was predicted by multiplying simulation-derived and corrected hours of vehicle travel (converted to seconds) by the applicable gram/second emission rates in Table 6-10. Table 6-11 presents the adjusted vehicle hours of travel and predicted emissions by pollutant for the observed peak-hour flows with and without ramp metering. Table 6-12 11 presents the adjusted vehicle hours of travel and predicted emissions by pollutant for the incident (lane closure) scenarios with and without ramp metering. The last column in each of the tables indicates the percentage change in emissions resulting from the implementation of ramp metering for each scenario.

Table 6-11
Predicted Change in Emissions by Pollutant
Volume-Adjusted CORSIM Simulation Runs
Metered and Non-Metered Non-Incident Conditions with Observed Peak-Hour Flows

Adjusted Vehicle Hours		Observed Flow Non-Metered	Observed Flow Metered	Simulated Impact of Ramp Metering
	NETSIM Total	93	316	239.6%
	Mainline Total	649	610	-6.0%
	Ramp Total	8	43	412.4%
	Total	750	969	29.1%
Ramps and Mainlines Only				
CO grams	Mainline Total	91,267	86,984	-4.7%
CO grams	Ramp Total	1,654	4,480	170.9%
	Total	92,920	91,463	-1.6%
NOx grams	Mainline Total	86,758	90,475	4.3%
NOx grams	Ramp Total	1,109	1,170	5.5%
	Total	87,867	91,645	4.3%
HC grams	Mainline Total	105,306	109,207	3.7%
HC grams	Ramp Total	1,031	1,426	38.3%
	Total	106,336	110,633	4.0%
System Totals				
CO grams	NETSIM Total	9,727	29,361	201.9%
CO grams	Mainline Total	91,267	86,984	-4.7%
CO grams	Ramp Total	1,654	4,480	170.9%
	Total	102,647	120,825	17.7%
NOx grams	NETSIM Total	2,298	3,947	71.8%
NOx grams	Mainline Total	86,758	90,475	4.3%
NOx grams	Ramp Total	1,109	1,170	5.5%
	Total	90,165	95,593	6.0%
HC grams	NETSIM Total	3,202	6,598	106.1%
HC grams	Mainline Total	105,306	109,207	3.7%
HC grams	Ramp Total	1,031	1,426	38.3%
	Total	109,538	117,231	7.0%

Table 6-12
Predicted Change in Emissions by Pollutant
Volume-Adjusted CORSIM Simulation Runs
Metered and Non-Metered Incident Conditions with Observed Peak-Hour Flows

		High Flow Non-Metered	High Flow Metered	Simulated Impact of Ramp Metering
Adjusted Vehicle Hours				
	NETSIM Total	93	317	239.4%
	Mainline Total	879	764	-13.1%
	Ramp Total	8	43	411.3%
	Total	981	1,124	14.5%
Ramps and Mainlines Only				
CO grams	Mainline Total	113,314	101,957	-10.0%
CO grams	Ramp Total	1,642	4,492	173.6%
	Total	114,956	106,450	-7.4%
NOx grams	Mainline Total	75,575	80,422	6.4%
NOx grams	Ramp Total	1,085	1,183	9.0%
	Total	76,659	81,604	6.5%
HC grams	Mainline Total	95,996	99,950	4.1%
HC grams	Ramp Total	1,007	1,443	43.3%
	Total	97,003	101,392	4.5%
System Totals				
CO grams	NETSIM Total	9,679	29,443	204.2%
CO grams	Mainline Total	113,314	101,957	-10.0%
CO grams	Ramp Total	1,642	4,492	173.6%
	Total	124,636	135,893	9.0%
NOx grams	NETSIM Total	2,219	3,937	77.4%
NOx grams	Mainline Total	75,575	80,422	6.4%
NOx grams	Ramp Total	1,085	1,183	9.0%
	Total	78,878	85,542	8.4%
HC grams	NETSIM Total	3,103	6,596	112.6%
HC grams	Mainline Total	95,996	99,950	4.1%
HC grams	Ramp Total	1,007	1,443	43.3%
	Total	100,106	107,988	7.9%

Figures 6-35 to 6-38 summarize, in graphic format, the HC and NOx emissions information provided in Table 6-16.

Figure 6-35

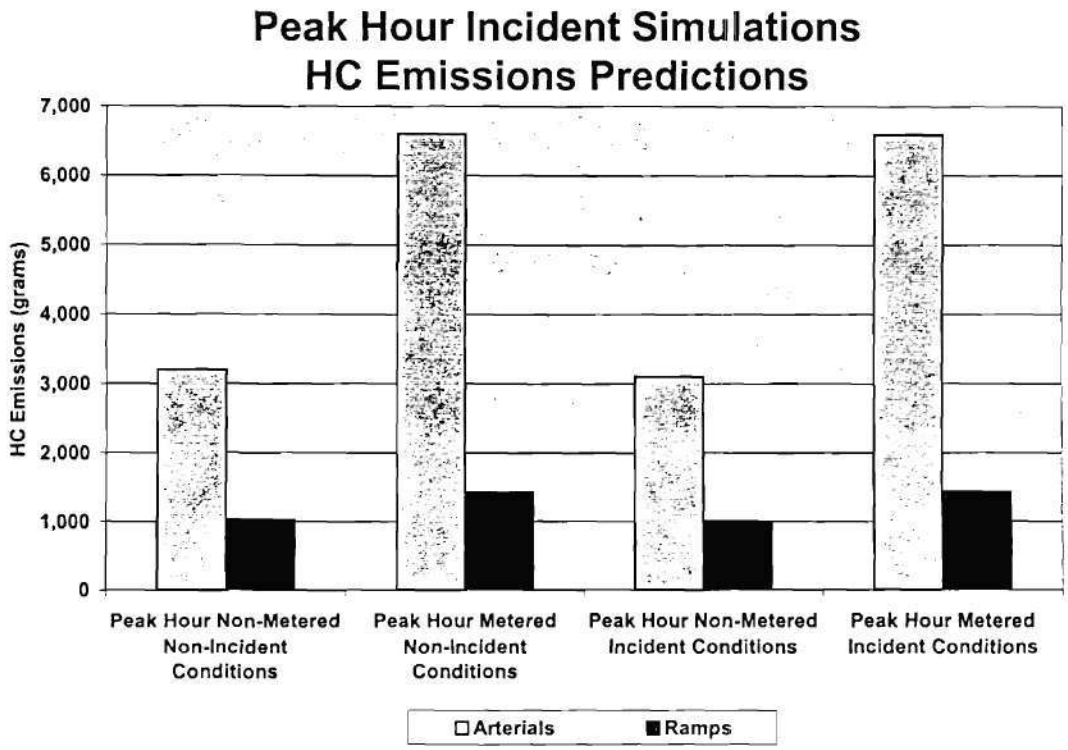


Figure 6-36

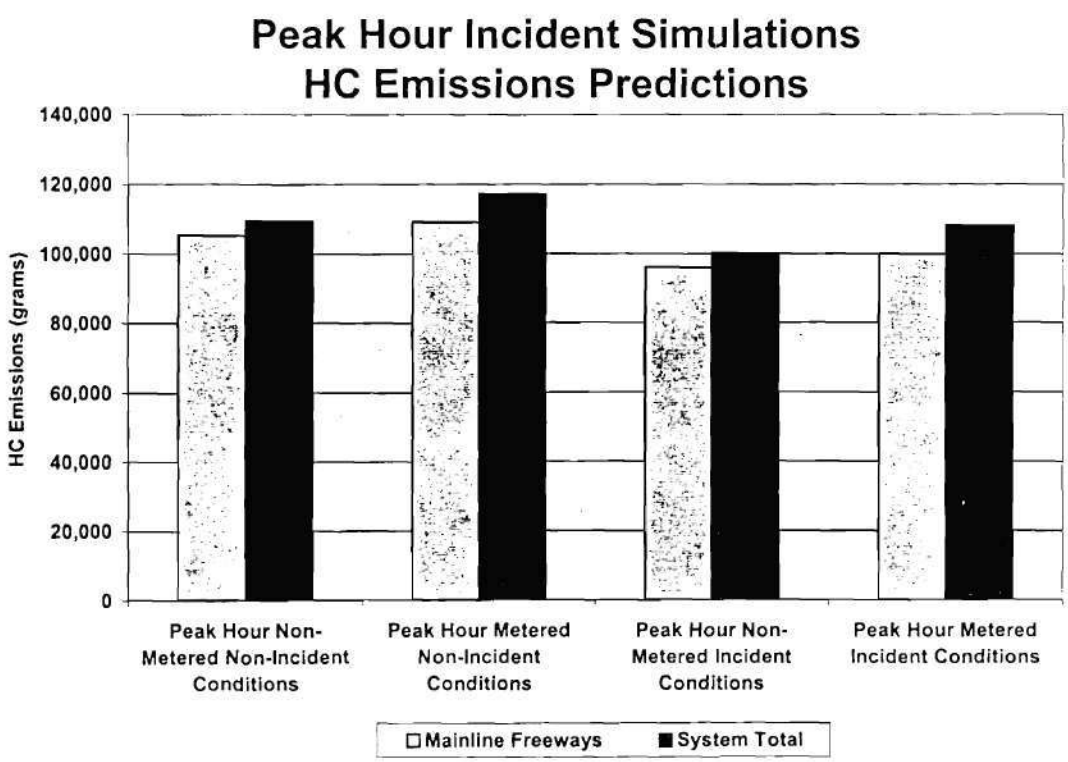


Figure 6-37

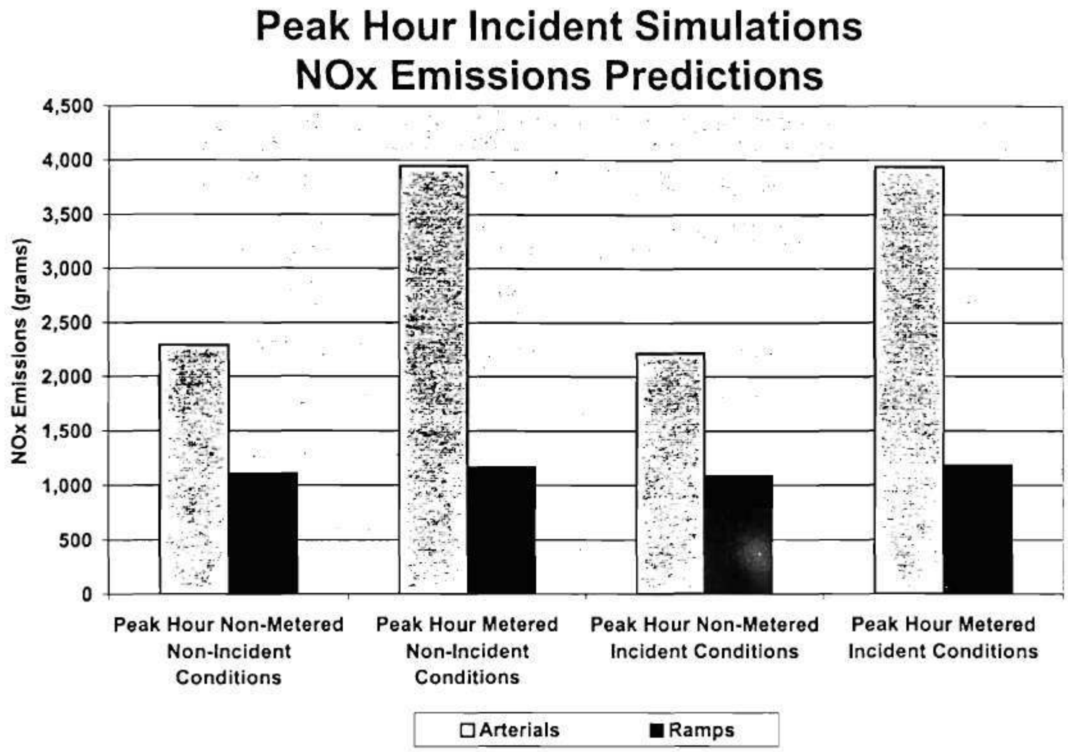
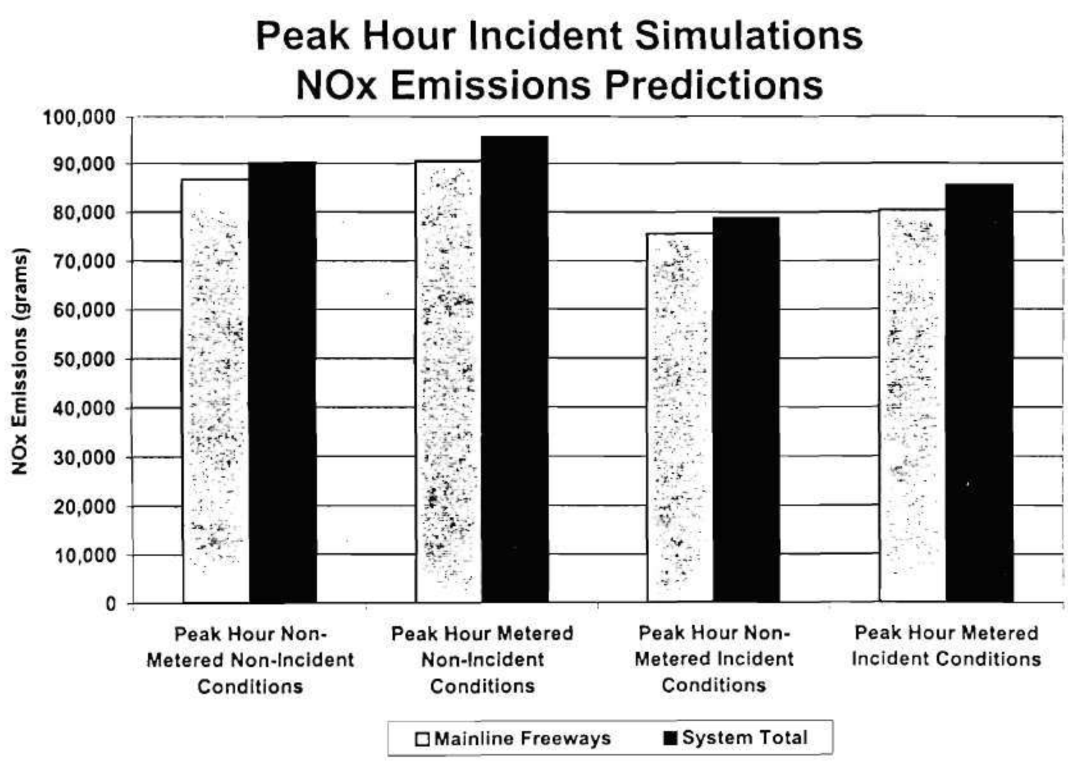


Figure 6-38



The lane closure simulations allowed the research team to examine the potential effects of ramp metering on a system that has begun to undergo flow breakdown conditions. The lane closure simulations support other research efforts demonstrating that ramp metering has a potentially significant impact on mainline average freeway speeds. Simulations of observed peak-hour flows indicated that metering would yield a small increase in average freeway speeds; from 53 mph to 55 mph (Table 6-8 and accompanying figures). However, simulations of peak-hour lane-closure conditions indicated that metering would increase average freeway speeds from 39 mph to 45 mph (Table 6-9 and accompanying figures). Simulations predict that ramp metering reduces mainline freeway travel times by 6% for normal peak-hour conditions and by 13% under lane closure conditions, indicating that ramp metering is even more effective at reducing travel delay under incident conditions.

Peak-hour simulation results corroborated previous 3-hour peak-period simulation results with respect to predicted changes in ramp operating speeds. However, one-hour simulations again predicted large changes in ramp speeds that were never observed in the field. However, the simulated lane closures do not affect arterial or ramp operations, only the operations of freeway traffic. Ramp meter timing and the physical characteristics of the ramps are the only variables affecting the flow of traffic onto the freeway segments from the arterials. Because travel ramps and arterial travel times remained constant across the non-lane-closure and lane-closure scenarios, the ramp simulation issues do not impact the comparative assessment of metering impacts across these non-lane-closure and lane-closure conditions.

As with the previous simulations for observed flow and high volume flow conditions, ramp meter operation under peak-hour and peak-hour lane closure conditions is predicted to yield higher emissions than leaving the meters off. Simulation of metering under observed non-lane-closure peak-hour conditions lead to a predicted 4% increase in combined mainline and ramp emissions of both HC and NOx compared to non-metered conditions. These reductions come with a relatively small increase in average speeds (less than 3 mph). Metering under peak-hour lane-closure conditions was predicted to increase combined mainline and ramp emissions of HC by 4% and NOx by 6.5%, compared to non-metered lane closure conditions. However, the increased HC and NOx emissions under lane closure conditions come with much larger predicted savings in mainline freeway travel time (approximately 13%). The findings indicate that operating these ramp meters under lane closure or other extreme congestion conditions may increase system emissions. Ramp emissions do appear to decline, but the small percentage increase in mainline emission rates (given the large volumes of vehicles) leads to significant overall mass emissions increases.

However, even though ramp meter operations under the modeled incident conditions were predicted to increase (HC emissions by 4% and NOx emissions by 6.5%), the mainline and ramp mass emissions after metering are still lower than they would be under non-incident conditions. For example, the simulation model predicted that metering under the lane-closure conditions would increase combined mainline and ramp NOx emissions from approximately 76,600 grams to 81,600 grams, which is still lower than the peak-hour non-incident non-metered emissions of 87,900 grams. Hence, one can argue that ramp metering under incident conditions does not constitute an emissions increase from a planning perspective, because the increase in mainline and ramp emissions does not put the facility emissions above emissions from normal operations. However, this assertion is not likely to hold true in cases where metering significantly disrupted the arterial systems to the point where emissions increases on the arterials dominate the analyses. Under any operating scenario, it is critical to ensure that ramp queues do not spill over onto arterials.

6.6 Summary of Simulation Results

The field observations and simulation runs, coupled with the MEASURE Aggregate Modal Model emission rates, indicate that ramp meter operations under the monitored conditions are likely to increase overall system emissions, while providing little benefit in travel time. Under high flow conditions, emissions from the system appear to increase after metering, but significant traffic flow improvements occur simultaneously. The simulation results support previous field studies indicating that the congestion-reduction benefits of ramp metering increase as travel conditions worsen. Under lane closure conditions, simulations indicate that meter operation provides even greater travel time benefits.

All of the simulation analyses for this study area indicate that emissions are likely to increase after metering is implemented. However, it is important to note that the emissions baseline, against which the emissions changes associated with metering should be compared, is a planning/policy decision. As mentioned earlier, the simulation model predicted that metering under the lane-closure conditions would increase NOx emissions from approximately 76,600 grams to 81,600 grams. However, the final emissions total after metering remains lower than the peak-hour non-incident non-metered emissions of 87,900 grams. Hence, one can argue that ramp metering under incident and extreme non-recurrent congestion conditions does not constitute an emissions increase from a planning perspective, because the facility emissions remain below those of normal operating levels.

6.7 Simulation Caveats

The traffic volumes predicted by the simulation modeling exercise roughly match the observed volumes from field data. This is because the simulation routines were constrained by appropriate entry node input volumes, based upon field measurements. The speed differences between simulated metered and simulated non-metered conditions are consistent with the basic assumption that ramp meters increase speeds on mainline freeway segments and reduce speeds at onramps and surface street arterials. However, the simulated speed and acceleration profiles for the observed volume simulations differed significantly from the vehicle activity patterns that were measured in the field using laser guns and chase vehicles.

Simulated ramp metering under observed peak-period and peak-hour conditions increased predicted system emissions for HC and NOx emissions. Note, however, that the simulation speed/acceleration profiles differed significantly from those observed in the field. The main differences between observed and simulated results appear in the speed/acceleration matrices, which significantly increased vehicle emission rates. Whereas the simulation speeds for the observed mainline freeway conditions hover in the range of 49 to 54 mph, the probe vehicle technique yielded average mainline speeds approximately 60 to 62 mph. Field observations with laser guns also recorded higher speed activity and more hard acceleration conditions under all ranges of speeds, leading to higher emissions under MEASURE estimations. The simulation model predicted lower metered and non-metered average speeds and emissions than were predicted using observed field data. The simulation also predicted greater percentage increases in emissions from ramp metering than were observed in the field, because the simulation predicted a smaller emissions baseline and larger increase in emissions relative to that baseline.

The simulation results provide information on overall system operations that considers the combined influence of all lanes (the faster moving left lanes speeds are averaged with the slower moving right lane speeds). However, the field observations offer a clearer understanding of lane-specific speed behavior. Probe vehicle and laser gun observations indicate that the specific lane where speed data are collected strongly influences mainline speed distributions. The disparity in observed versus simulated average speeds (approximately 6 mph to 15 mph) is disconcerting. The CORSIM car following routines that predict speed and acceleration and the lane change algorithms require further refinement, especially for ramp operations and high-speed freeway operations (see discussions earlier in this chapter).

The field measurement and simulation speed-acceleration distributions also differ significantly in the acceleration plane. Hard acceleration activity on ramps is over-predicted by the simulation models across a variety of low to moderate speeds as well as high speeds. Moreover, predicted hard deceleration rates in the simulations were not observed in the field. In examining the simulation-predicted speed/acceleration profiles, the specific acceleration cutpoints used in the car following appear as ridge patterns on the surface, especially in the -5mph/sec range. Differences between observed and simulated operating characteristics were also obtained in studies of intersection modeling simulation (Hallmark, et al., 1999). However, on Atlanta's signalized arterials, the simulation models under-predicted hard acceleration events. The ramp metering simulation results also support the assertion by Hallmark et al. (1999) that further improvements to the CORSIM car following routines should be made before CORSIM is used as a stand-alone activity generator for modal emissions modeling. Although the simulation models provide reasonable estimates of traffic flow, the speed and acceleration rate relationships imbedded in the CORSIM car following routines do not provide accurate estimates of onroad acceleration activity.

The simulation run emissions predictions support the field findings, to the extent that emissions from the metered system were projected to increase compared to the non-metered system. However, the simulation modeling results come with a strong caveat. There are no field observations available to confirm the predicted changes in speed/acceleration profiles under high volume or lane closure conditions. The corridor in question is simply not capable of experiencing sufficient travel demand to achieve flow breakdown. In addition, only the MEASURE Aggregate Modal Model emission rates were tested with the field and simulation data. Additional testing is recommended with MOBILE6 (an improved average speed model), the UC Riverside physical model, and the European VETO emissions microsimulation model (models that predict emissions from each individual vehicle speed trace) to corroborate predicted emissions changes.

CHAPTER 7
EMISSIONS MEASUREMENTS

Emissions of carbon monoxide (CO), reactive hydrocarbons (HC), and nitrogen oxides (NO_x) from motor vehicles have the potential to adversely impact human health and the environment by contributing to the formation of photochemical smog, acid deposition, regional haze and elevated CO levels. Knowledge of the relative contributions of different types of motor vehicles to each type of emission and the sensitivity of these emissions to characteristics such as vehicle age, maintenance, activity patterns and traffic control measures is important to urban and regional air quality control and the protection of human health and the environment. This evaluation is best done on the roadways where the actual emissions take place and modern vehicle remote sensing and meteorological flux technologies enable these measurements to be made.

7.1 Overall Experimental Design

The I-75 corridor, immediately north of the Atlanta central business district, previously described in Chapter 4, was selected as the study site for this research. As this corridor was selected for other characteristics (e.g., the presence of ramp metering) the location was not optimal for emissions measurements largely due to local topography. Nevertheless, sufficiently suitable sites were identified to produce effective measurements on more than twenty days during the study period.

The twin objectives of this portion of the study were met using two independent measurement approaches. Emissions from vehicles operating on the ramps were evaluated using on-road optical remote sensing. The remote sensing technology is capable of measuring exhaust emissions of many thousands of vehicles per day and provides a practical approach for routinely characterizing on-road vehicle emissions. This approach has the advantage of identifying emissions from individual vehicles but is limited to measurements at suitable fixed locations.

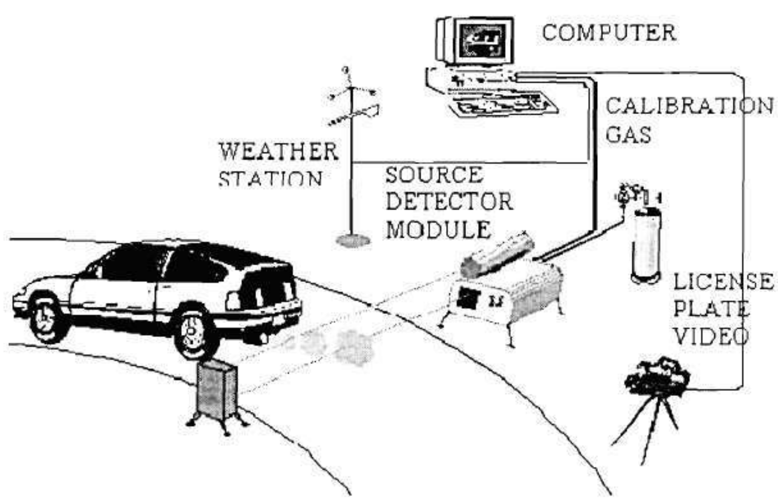
The Air Quality Laboratory (AQL) of the Georgia Institute of Technology (GIT) conducted the on-road motor vehicle emissions portion of the I-75 Ramp Metering Project using two Remote Sensing Devices (RSD) employing Non-Dispersive Infrared (NDIR) spectroscopy for measurement of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2). The objective of these measurements was to characterize the on-road emissions of the fleet-at-large for the five north-bound entrance ramps onto I-75 within the study area. These were the north-bound ramps at Northside Drive, Howell Mill Road, Moores Mill Road, West Paces Ferry Road, and Northside Parkway. The specific sampling sites on these ramps were selected by AQL and approved by the Georgia Department of Transportation prior to the field collection effort. These measurements are described in section 7.2 below.

Emissions from the mainline were evaluated using *in-situ* measurements made above the roadway. This latter method allows direct measurement of total emissions fluxes but does not identify the individual vehicles responsible for the emissions. The complementary nature of these two techniques provides a powerful approach to evaluating both total emissions and emissions distributions from fleets. In addition, it provides a valuable "reality check" on the associated emissions modeling. These results are summarized in section 7.3.

7.2 Remote Sensing Measurements

Remote Sensing systems are based upon the absorption of light by the individual constituents that make up the vehicle exhaust. Infrared (IR) spectroscopy is used to measure concentrations of CO and HC while ultraviolet (UV) spectroscopy is used to measure NOx. A schematic diagram of a remote sensing device (RSD) making on-road vehicle exhaust measurements appears in Figure 7-1 below. Light from a source placed along the roadway is transmitted to a mirror located on the opposite side. The light is reflected back to a co-located detector. The measurement cycle is initiated by the passage of a vehicle that interrupts this beam of light. After the vehicle has passed, the gases in the vehicle's exhaust reduce the amount of light received by the detector compared with that measured immediately before or well after the passage of the vehicle. This reduction in received light (absorption) in used to quantify the concentration of the individual pollutant compounds through a calibration process.

Figure 7-1
Remote Sensing On-Road Setup



In addition to the source and detector, remote sensors normally include a camera system to record vehicle license tags to aid in identifying individual vehicle characteristics. The systems are also usually equipped with meteorological stations and/or vehicle speed/acceleration systems, which are important in interpreting exhaust measurements due to the influence of vehicle load and environmental conditions. The RSD technology is capable of measuring the CO, HC, and NO_x exhaust emissions of many thousands of vehicles per day and provides a practical approach for routinely characterizing on-road vehicle emissions. As such, remote sensing has several potential regulatory uses: determining fleet average emissions for inventory purposes, characterizing fleet emissions distributions to evaluate control programs, comparing with other fleets for benchmarking purposes and, as in this case, in evaluating traffic control measures.

Previous remote sensing studies have indicated that most of the measured on-road emissions (>50%) come from a disproportionately small percentage of the vehicles (approximately 10%). This has been shown to be true for CO, HC and most recently for NO_x. Since the remote sensing signal can be integrated with a video image of the license plate of the passing vehicle, RSD can also be used to identify high emitters requiring immediate attention and clean vehicles that may be candidates for I/M exemption. With these potential applications, several states are considering adopting remote sensing as a supplement to their inspection and maintenance programs (I/M).

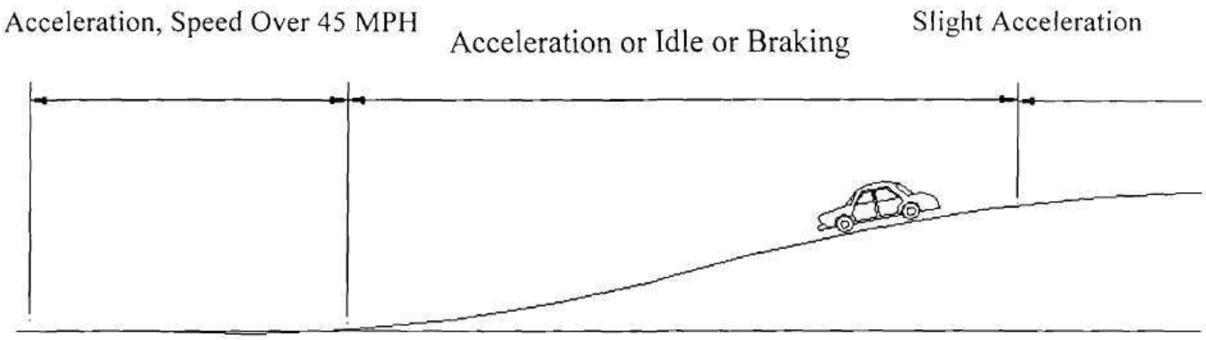
Despite these advantages, the RSD approach is not without its drawbacks. Most notably, remote sensing measurements are only a snapshot (< 1 sec) of the emissions of a vehicle. Vehicle emissions are highly variable both between vehicles and in time. Thus the greatest value theoretical value of remote sensing is in a statistical sense where numerous observations can be averaged to yield accurate observations of fleet characteristics. Secondly, RSDs have specific siting requirements regarding visibility, single lane operation, absence of maneuvers, no cold-start operations, etc., that severely limit the range of locations that can be observed by remote sensing. These factors place a premium on site selection to ensure that the available sites are both representative of controlled driving operations and the actual operational fleet in the larger region. These factors are discussed later in the text. Additionally, in its current form, RSD technology is limited to measurements of tailpipe emissions and provides no information regarding the performance of vehicles in regard to evaporative emissions and running losses.

7.2.1 Site Selection

Based on previous experience, the best sites are located on highway entrance ramps where major roads provide a high traffic flow to the highway. Ideally, sites should have a positive slope of 1 to 3 percent and that the vehicles pass the site with a slight acceleration rather than on idling or braking. These conditions ensure that the vehicle is operating under moderate load and thus the emissions are representative of the vehicle's typical emissions. These conditions cannot always be met at sites that meet the need for good fleet representation and techniques have been developed to use sites having different characteristics. Figures 7-2, 7-3, 7-4 and 7-5 represent typical configurations of single lane ramps suitable for remote sensor setup and operation.

Figure 7-2 shows a typical entrance ramp to a highway having a negative slope. In this case, the driver's behavior is typified by a slight increase in speed, then transitions from acceleration to idle or braking and then accelerates again to merge with the traffic moving at highway speed. In this situation, the upper portion of the entrance ramp does not result in accelerations adequate for sampling. The middle of the ramp, or the maximum negative slope, is conducive to an inconsistent driver behavior resulting in highly variable emissions readings. At the bottom of the ramp, vehicles tend to accelerate to speeds exceeding 45 miles per hour causing the exhaust plume to dissipate too quickly for adequate measurement. This scenario is generally used only when more suitable option is not available

Figure 7-2
Negative Entrance Slope Scheme



Figures 7-3, 7-4, and 7-5 show other ramp configurations for remote sensing sites. Exit ramps are often characterized by high-speed operations followed by braking that often makes them undesirable. A notable exception is a ramp with a circular or semicircular cross-section (cloverleaf) that forces the driver to slow down to 25 – 35 MPH before they begin accelerating again. A typical exit with this kind of curve is shown in Figure 7-5.

Figure 7-3
Positive Slope Entrance Scheme - Cross-Section View

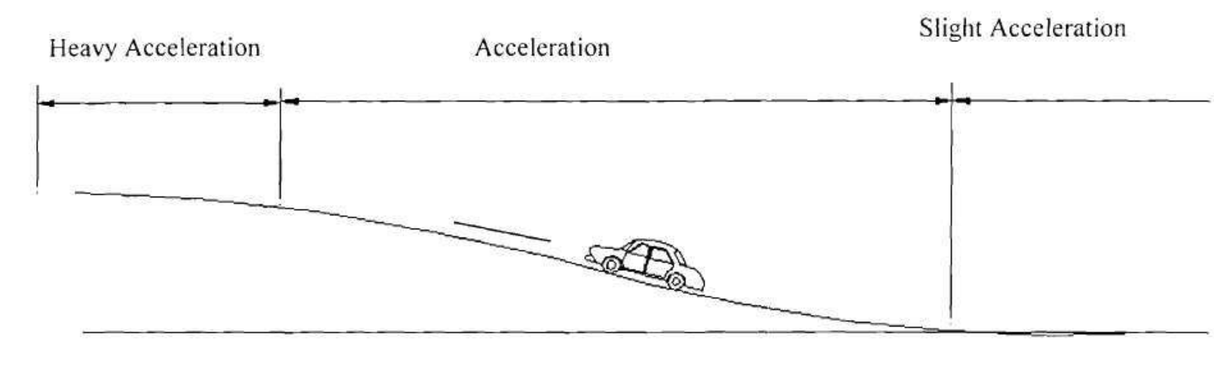


Figure 7-4
Entrance and Exit Scheme

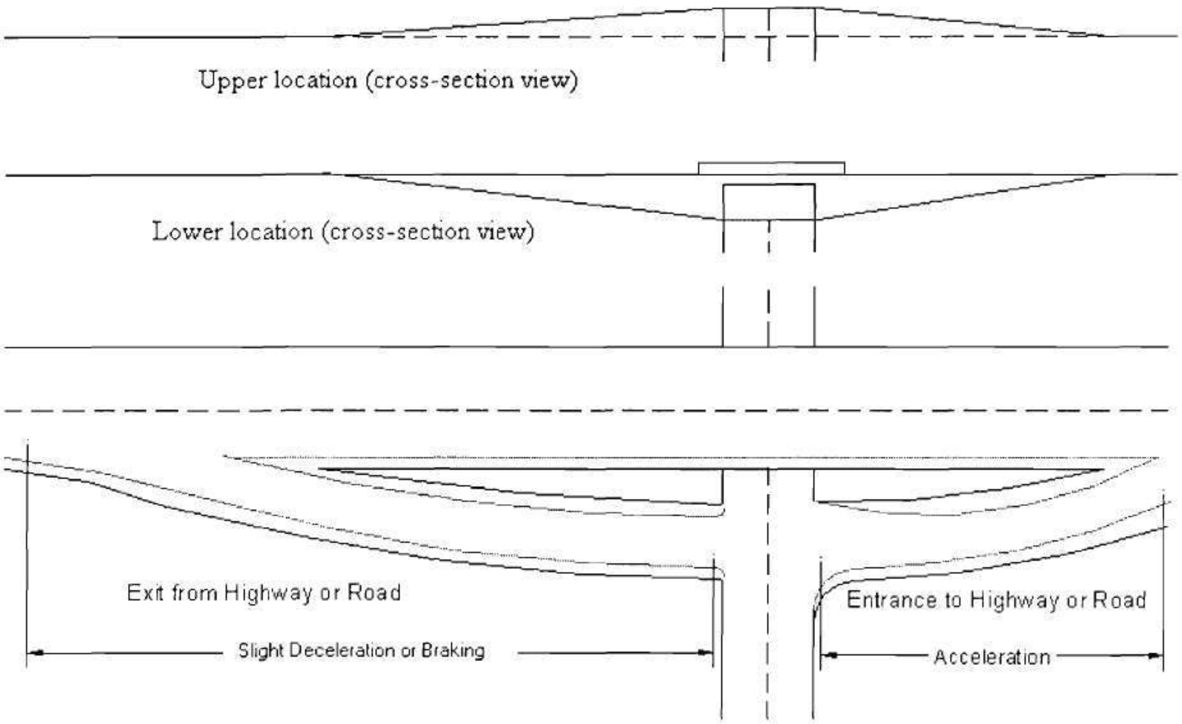
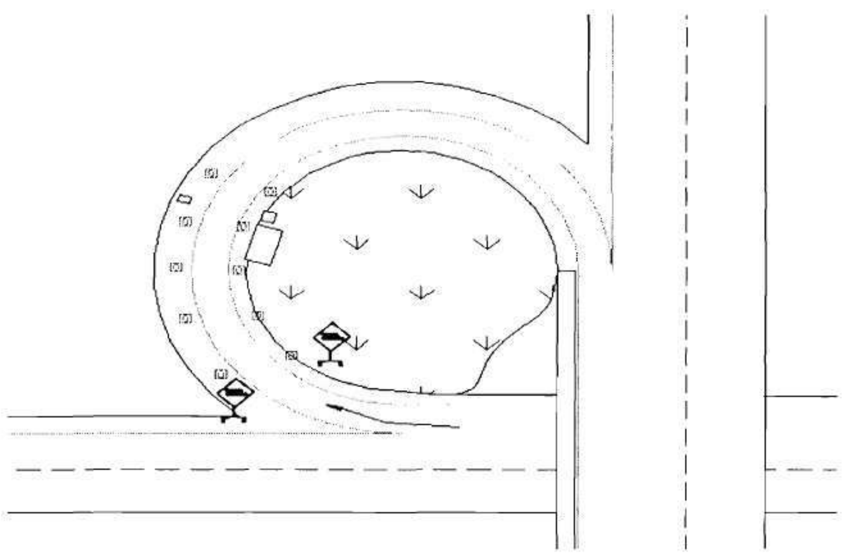


Figure 7-5
Curved Exit from Highway or Road



All of the sites selected for the GDOT Ramp Metering Study had favorable site geometry with near-zero or positive slopes, limited accelerations and manageable vehicle speeds. The most notable problems were associated with high vehicular speeds that reduced the number of valid readings at several of the sites. This problem led to moving the location of one site during the field operation. In no case, however, was the impact sufficiently large to impact either data analysis or interpretation.

While small-scale effects, such as site geometry, are important to achieving valid remote sensing readings, the overall distribution of sites is equally important to producing data that can be effectively interpreted.

7.2.2 Site Descriptions

Table 7-1 below gives a complete description of the position of the remote sensing equipment for each of the five data collection sites. In addition, the local road grade for each site is reported.

Table 7-1
Description of Site Locations

Site Name	Site Location	Position of Remote Sensor	Grade
TLS1	Northside Drive	At the end of ramp, 50 ft after ramp traffic light	-1.5%
TLS2	Howell Mill	At the beginning of ramp, 400 ft before ramp traffic light	-2.0%
TLS3	Moores Mill	At the beginning of ramp, 300 ft before from ramp traffic light	0.0%
TLS4A	West Paces Ferry	At the beginning of ramp, 200 ft before ramp traffic light	0.5%
TLS5	Northside Parkway	In the middle of a very long ramp, 1500 ft before ramp traffic light	1.0%

Schematic drawings for the location of the remote sensor are illustrated in Figures 7-6 through 7-10. These diagrams illustrate where the remote sensors are located at each of the sites with respect to the I-75 entrance ramps as well as with respect to the traffic lights.

Figure 7-6
Northside Drive Site Map

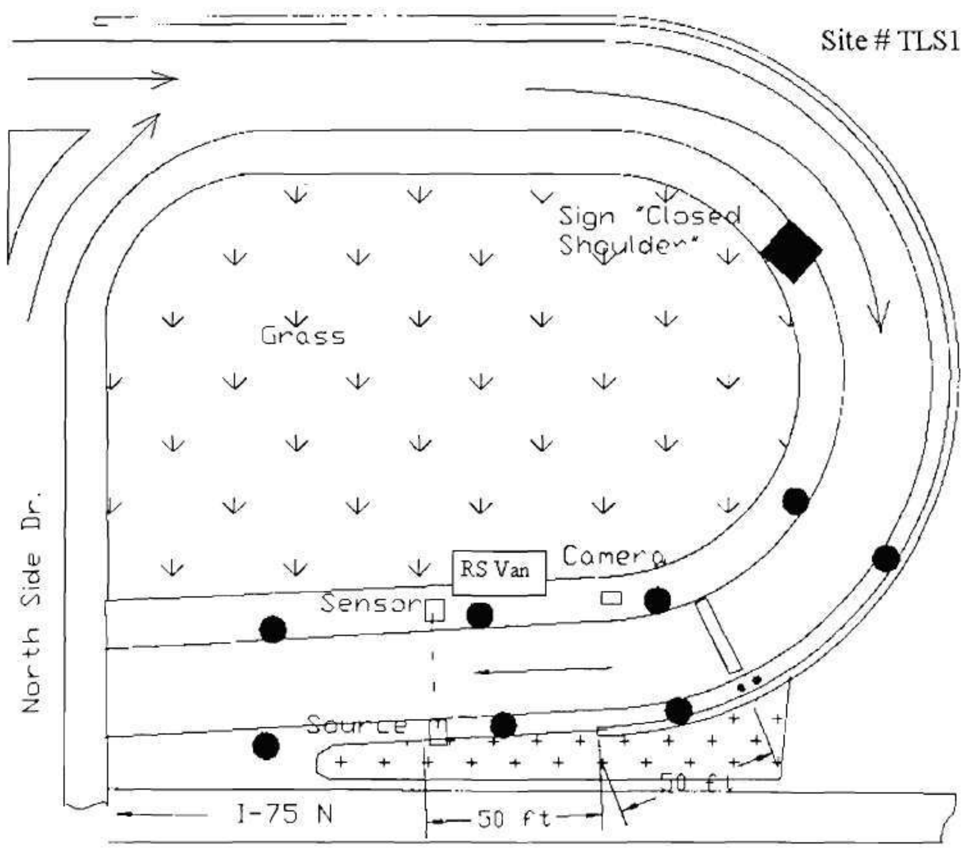


Figure 7-7
Howell Mill Road Site Map

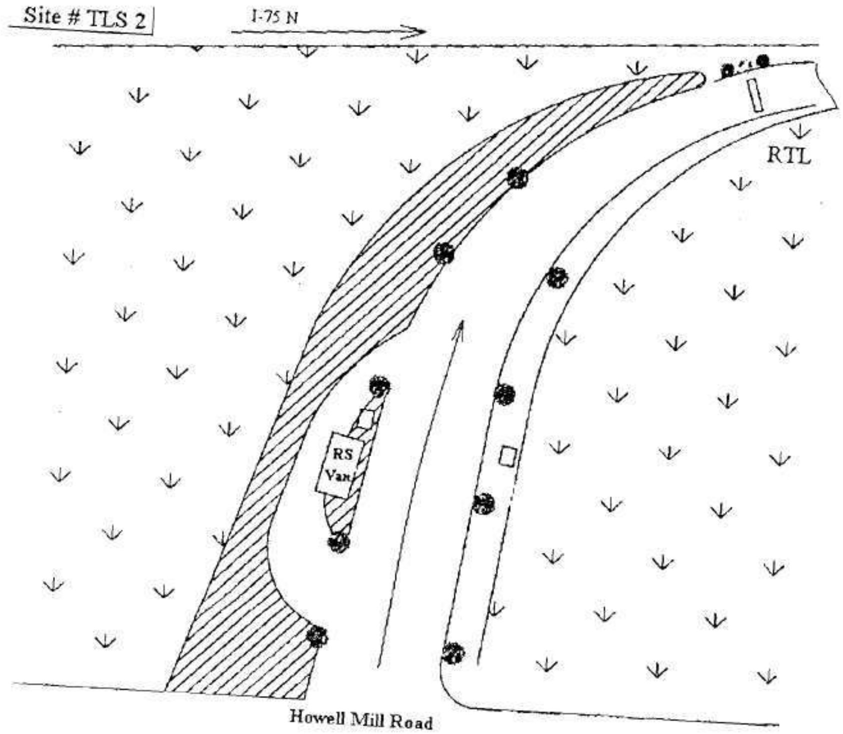


Figure 7-8
Moores Mill Road Site Map

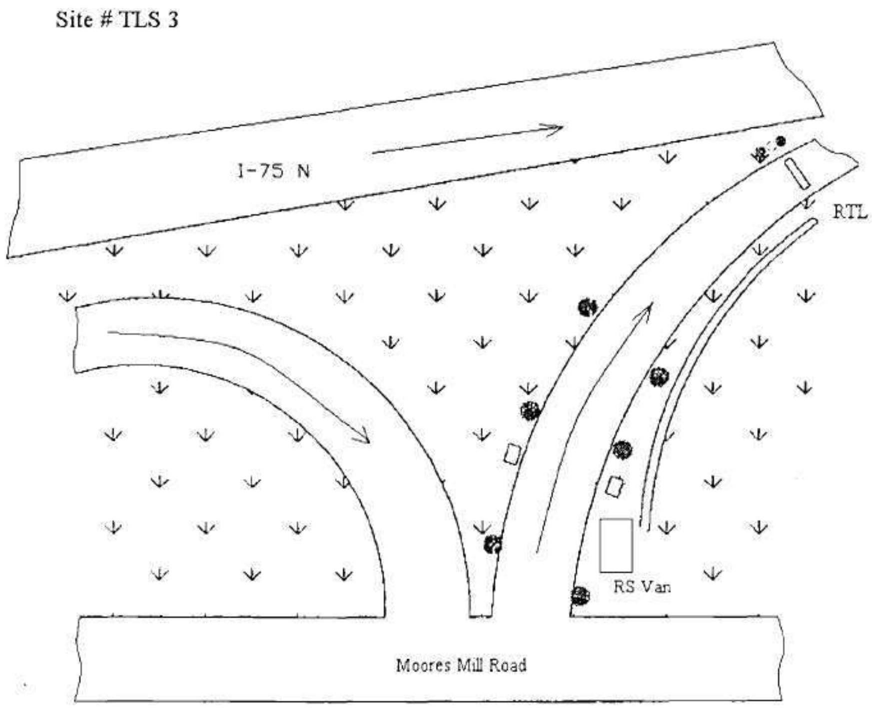


Figure 7-9
West Paces Ferry Road Site Map

Sites TLS 4A, TLS

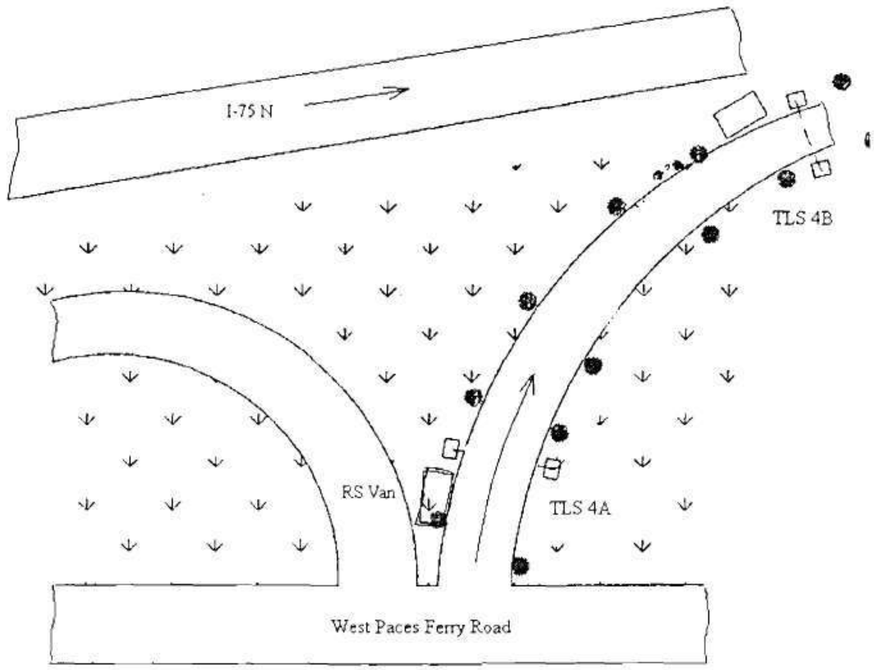
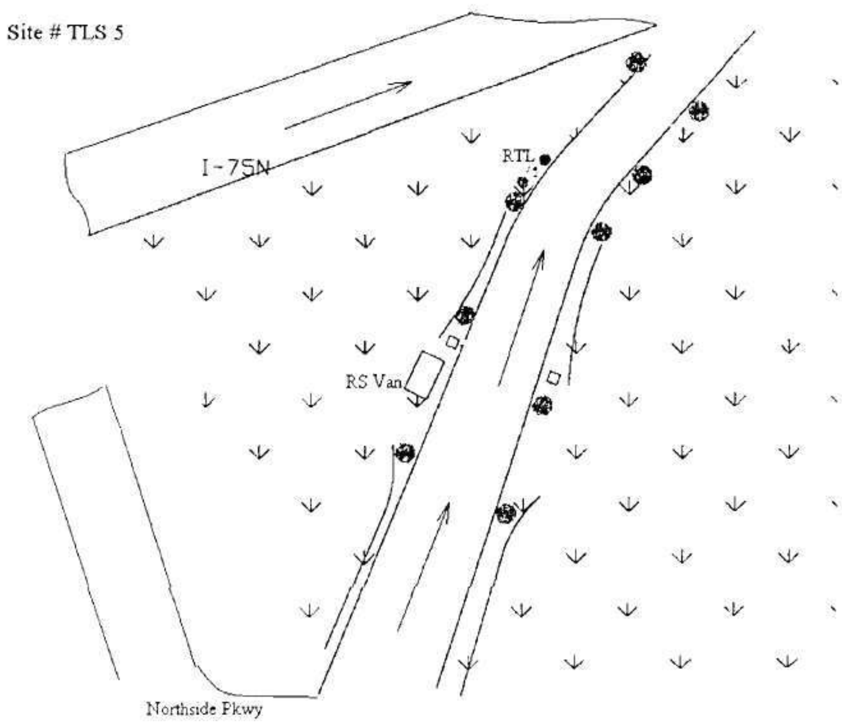


Figure 7-10
Northside Parkway Site Map



7.2.3 Data Collection

To collect emissions samples throughout the study, the research team used two remote sensors: 1) the SmogDog™ developed by the Hughes Santa Barbara Research Center (produced in 1994) and 2) the RSD3000 developed by Environmental Systems Products (produced in 1998). Both remote sensors are able to collect data on carbon monoxide (CO) levels, carbon dioxide (CO_2) levels and hydrocarbon (HC) levels. In addition, the RSD 300 remote sensor is equipped with a ultraviolet channel to measure NOx concentrations as well as equipment to record vehicles speeds, and acceleration rates. These units underwent multi-point calibrations both before and after the sampling at AQL's Hopkins Laboratory and underwent field tests immediately prior to deployment at the manufacturer's (Envirotest) facility in Hartford, Connecticut.

The RSD 300 and Smog Dog remote sensors differ in their design, methodology of concentration calculation, and rules of data validation. As a result, their direct CO readings are quite close at intermediate concentrations (0.6 – 1.5 %), but yield readings that differ up to 20 – 30 % for lower and higher concentrations. To account for this difference, the researchers developed a procedure to correct the data and make the results from the two remote sensors directly comparable with uncorrected differences of less than 5% between the two sensors. All of the results in this report are represented in these comparable "SmogDog" units. Measurement of the four exhaust gases, speed, and acceleration of the passing vehicle together with a digital image of the license plate comprised a valid remote sensing record.

Sampling took place over a six-week period between mid-May and the end of June 1999. During the data collection period, 47,079 vehicles triggered the RSD. Of these, 30,273 vehicles had readable license plates with valid CO values. Table 7-2 illustrates the distribution of valid data measurements across the sites.

Table 7-2
Total Number of Valid Measurements by Site

Site Number	Site Name	Count
TLS1	Northside Drive	9935
TLS2	Howell Mill	4005
TLS3	Moores Mill	3091
TLS4A	West Paces Ferry	6216
TLS5	Northside Parkway	7026

For the I-75 ramp metering study, the data collection process was enhanced by the use of a newly implemented software package developed by AQL. The software, known as Analyzer, enabled seamless importation of the data generated by the remote sensing instrument directly into a Microsoft Access database. This allowed for a preliminary field analysis of the data collected each day. The field analysis included a preliminary evaluation of CO, HC, NOx concentrations, vehicle speed, acceleration and major statistics such as mean and standard deviation. A complete description of the field data collected can be found in Table 7-3 below.

TABLE 7-3
Description of Site Characteristics

Site Name	Site Location	Vehicles per hour (9AM-10AM)	Acceleration (9AM-10AM)	Speed, MPH (9AM-10AM)
TLS1	Northside Drive	390	1.6 - 3.4	28 - 35
TLS2	Howell Mill	410	1.5 - 3.5	22 - 26
TLS3	Moores Mill	220	1 - 2.5	23 - 28
TLS4A	West Paces Ferry	310	0 - 1.2	23 - 28
TLS5	Northside Parkway	430	-0.2 - 2	30 - 37

Table 7-4 shows the schedule of measurements and numbers of interpreted readings for each day at off-peak time, before 15:30, when ramp traffic lights were off, and at-peak time, between 15:30 and 18:30, when ramp traffic lights were active.

Table 7-4
Schedule of Measurements and Volume of Collected and Processed Results

Date	Instrum	Site Num	Start Time	Finish Time	Beam Blocks	Interpreted Records	Records OffPeak	Records AtPeak
5/11	Smog Dog	TLS1	8:24	18:47	4161	2846	1483	1363
5/12	Smog Dog	TLS2	8:26	17:40	3772	2239	1605	634
5/14	Smog Dog	TLS3	8:24	17:30	2400	1534	1144	390
5/18	Smog Dog	TLS4A	7:57	17:03	3334	2217	1655	562
5/19	Smog Dog	TLS5	8:47	18:41	5522	3682	2035	1647
5/19	RSD	TLS5	8:37	18:38	5111	3344	1886	1458
5/25	Smog Dog	TLS1	8:43	18:31	4003	2848	1522	1326
5/26	Smog Dog	TLS2	8:29	10:21	772	331	331	0
5/27	Smog Dog	TLS3	9:03	18:30	2467	1557	966	591
5/28	Smog Dog	TLS4A	8:41	18:15	3723	2373	1651	722
6/2	Smog Dog	TLS1	8:51	18:11	5256	3398	2027	1371
6/17	RSD	TLS2	13:01	18:15	2501	1435	607	828
6/18	RSD	TLS4A	10:47	18:30	2774	1626	1035	591
6/30	RSD	TLS1	11:21	15:07	1283	843	843	0
				Totals	**47079**	**30273**	**18790**	**11483**

7.2.4 Data Analysis for Fleet Composition

Following the field measurements, the entry of license plate information into the emissions records was performed by GIT data entry personal between July and September 1999. Approximately 47,000 raw RSD measurements provided approximately 30,000 valid records. These data were then matched with the Georgia Department of Revenue Vehicle Registration database. As a result of this matching process, the vehicle identification number (VIN) was recovered for each valid record. The VINs were decoded using a commercial VIN decoding package (Radian) yielding information regarding engine parameters, emissions control equipment, vehicle model year, vehicle type and other variables. These data were merged with the remote sensing records to produce the consolidated remote sensing database.

Based on a match with the Georgia motor vehicle registration database, the vehicle distribution by vehicle type is indicated in Tables 7-5 and 7-6. The number of vehicles having the registration type of "Car" or "Truck" suggests a sufficient sample set to perform a more detailed statistical analysis.

Table 7-5
Classification of Vehicles

Number	Cars	Trucks
1	Subcompact/Compact	Pickup
2	Midsize	Bus
3	Fullsize/Luxury	Commercial Tags
4	Sports Car	SUV
5	Other	Van

Table 7-6
Distribution of Records by Vehicle Type and Category

Vehicle Type	Category	Number of Records
Car	Subcompact/Compact	4706
Car	Midsize	5900
Car	Fullsize/Luxury	5143
Car	Sports	1064
Car	Other	2296
Truck	Pickup	4463
Truck	Bus	65
Truck	Commercial	216
Truck	SUV	4396
Truck	Van	1634

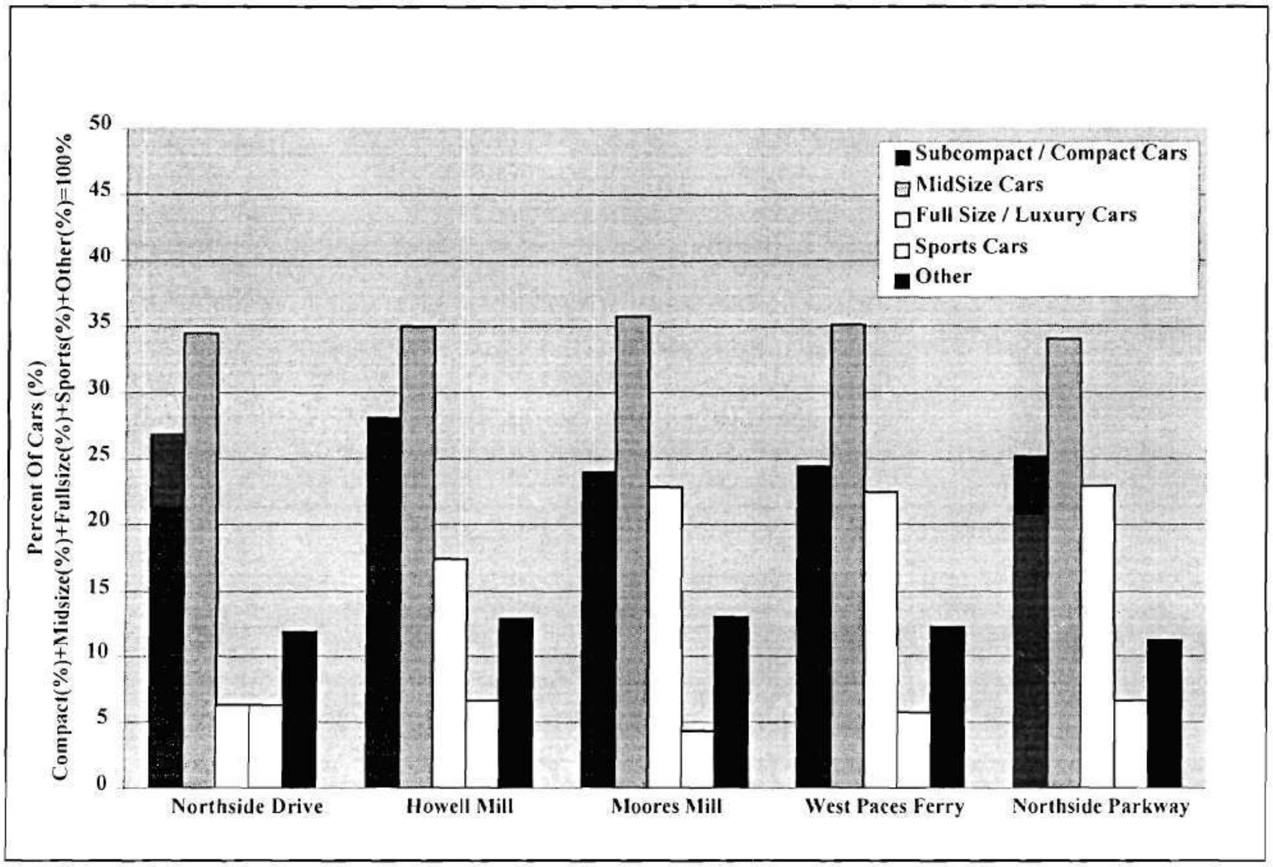
Table 7-7 displays the types of cars that are assigned in the subcompact/compact, midsize, full-size/luxury, and sports car categories.

Figure 7-11 shows the distribution of car types at each site. Obviously, the research team observed more mid-size cars at each site than any other type of car. The second most popular car type at each site was the subcompact/compact classification. However, the discrepancy between the number of compact cars and luxury/full-size cars at each site varied by site. For example, many more compact cars were observed at Northside Drive and Howell Mill than luxury/full size cars.

Table 7-7
Car Classification Categories

Subcompact/ Compact	Mid-Size Cars	Full Size Cars	Sports Cars
Acura Integra	Acura TL	Acura RL	Chevrolet Camaro
Audi A4/S4	Audi A6	Acura Legend	Ford Mustang
Chevrolet Cavalier	Buick Century	Audi A8	Honda Prelude
Chevrolet Metro	Buick Regal	All BMW's	Lexus SC 300/400
Chevrolet Prizm	Cadillac Catera	Buick LeSabre	Mazda Miata
Chevrolet Sebring	Chevrolet Lumina	Buick Park Avenue	Mitsubishi Eclipse
Dodge Avenger	Chevrolet Malibu	Cadillac DeVille	Pontiac Firebird
Dodge Neon	Chrysler Cirrus	Cadillac Eldorado	All Porsches
Ford Escort	Dodge Stratus	Cadillac Seville	Toyota Celica
Ford Probe	Ford Contour	Chevrolet Caprice	Toyota MR2
Ford Tempo	Ford Taurus	Chevrolet Impala	Toyota Supra
Geo Metro	Ford Thunderbird	Chevrolet Monte Carlo	
Geo Spectrum	Honda Accord	Chrysler Concorde	
Geo Storm	Hyundai Sonata	Chrysler LHS	
Honda Civic	Infiniti I30	Chrysler New Yorker	
Hyundai Accent	Mazda 626	Dodge Intrepid	
Hyundai Elantra	Mazda Millenia	Ford Crown Victoria	
Infiniti G20	Mercury Cougar	Infiniti Q45	
Kia Sephia	Mercury Mystique	All Jaguars	
Mazda Protege	Mercury Sable	Lexus ES300	
Mazda 323	Mitsubishi Diamante	Lexus GS300/400	
Mitsubishi Galant	Nissan Altima	Lexus LS400	
Mitsubishi Mirage	Nissan Maxima	All Lincolns	
Nissan Sentra	Oldsmobile Cutlass	All Mercedes	
Nissan Stanza	Oldsmobile Intrigue	All Saabs	
Plymouth Neon	Plymouth Breeze	Mercury Grand Marquis	
Pontiac Sunfire	Pontiac Grand Am	Pontiac Bonneville	
All Saturns	Pontiac Grand Prix	All Rolls Royces	
Subaru Impreza	Subaru Legacy	All Volvos	
Suzuki Esteem	Toyota Camry		
Suzuki Swift	Toyota Solara		
Toyota Corolla			
Toyota Tercel			
All Volkswagens			

Figure 7-11
Car Classifications by Site



On the other hand, at the Moores Mill, West Paces Ferry, and Northside Parkway sites, the distribution of compact and luxury/full size cars was much more comparable. This result is consistent with the hypothesis of a wealthier demographic at these three sites than Northside Drive and Howell Mill. Figures 7-12 and 7-13 break down frequencies of the car types (i.e., subcompact/compact, mid-size, full-size/luxury, sports cars, and other) by on-peak and off-peak time intervals, respectively.

Figure 7-12
Comparison of Car Flows by Site during Off-Peak Hours

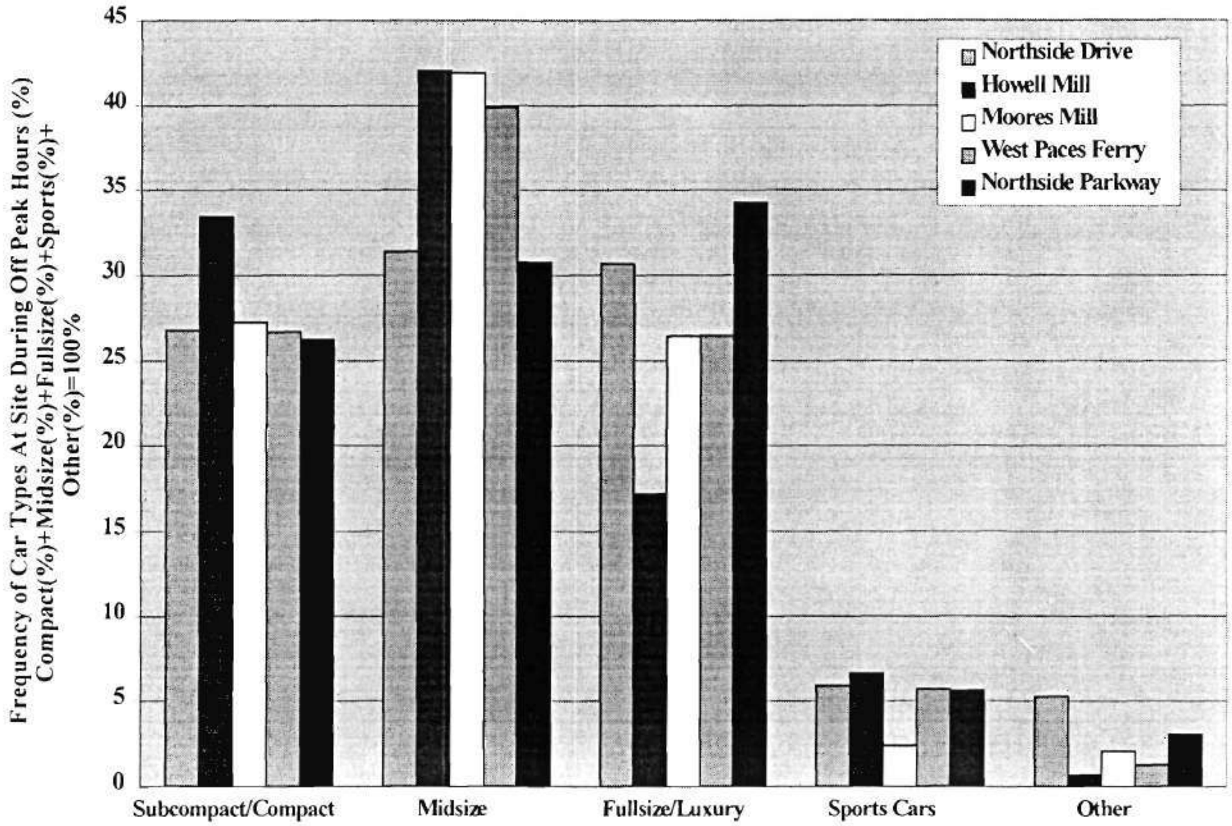
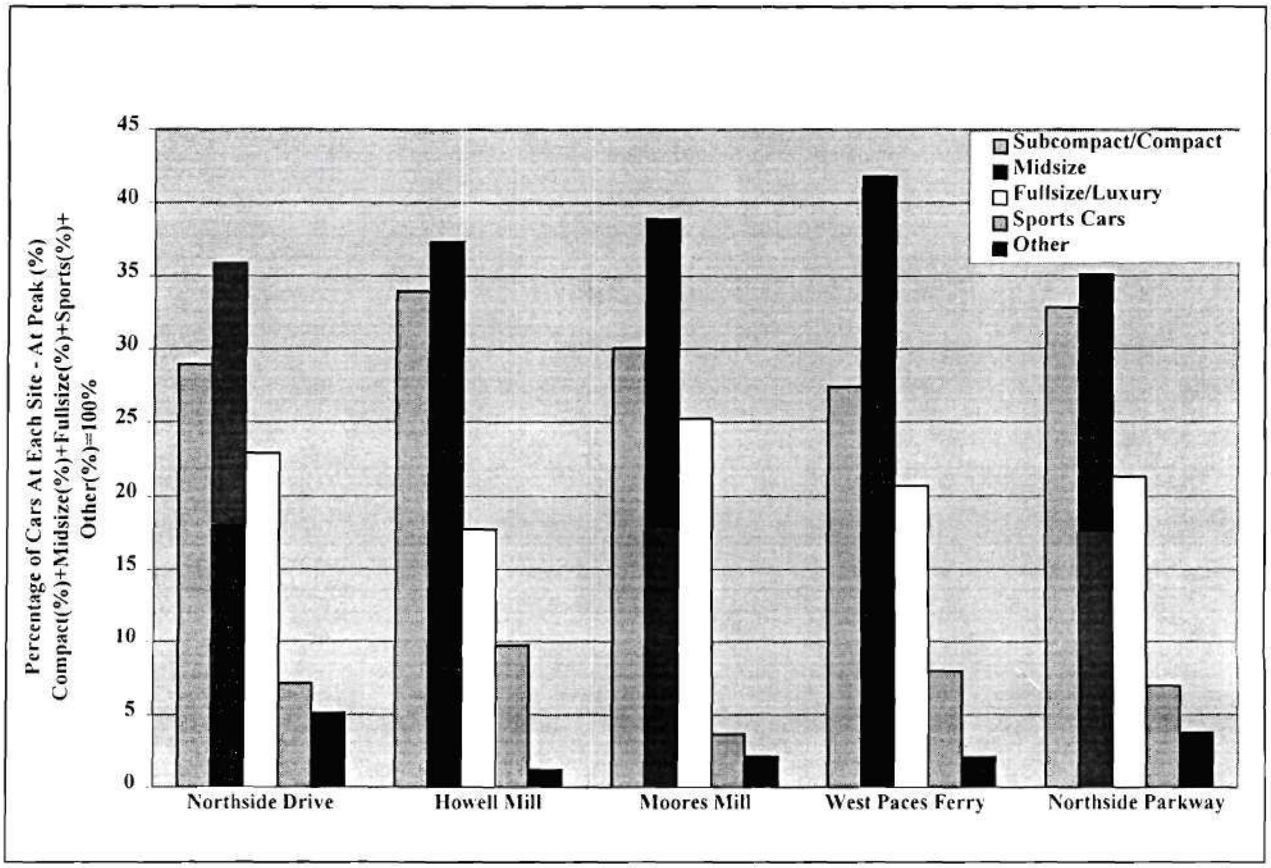


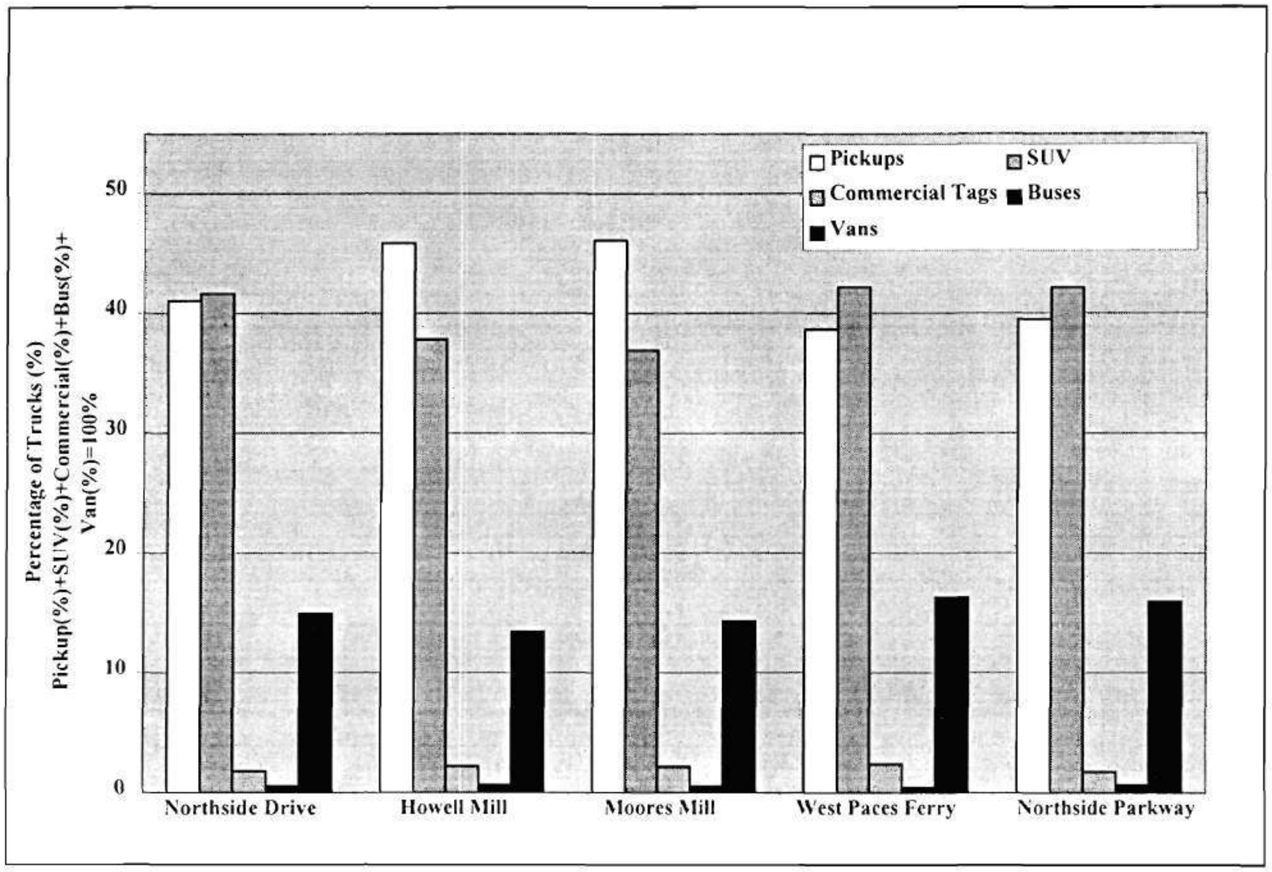
Figure 7-13
Comparison of Car Type Frequencies during Peak Hours by Site



During peak hours, there are higher percentages of mid-size cars at each site with subcompact/compact cars coming second. During off-peak hours, Howell Mill, Moores Mill, and West Paces Ferry still have more midsize cars than any other type. Yet, at Northside Drive during off-peak hours, mid-size and full-size/luxury cars represent almost the same percentage of the fleet composition. At Northside Parkway (i.e., Mount Paran Road), during off-peak hours, full-size/luxury cars compose the largest portion of the fleet.

Figure 7-14 shows the distribution of truck types at each site. This figure illustrates that each of the five sites were dominated by pickups and SUVs. The third most popular truck type at each of the sites was the van category. In agreement with our hypothesis that the West Paces Ferry and Northside Parkway sites represent a wealthier demographic, we find there are more SUVs than pickups at both of those sites. However, we also expected Moores Mill to represent a wealthier demographic and we expected SUVs to again dominate the truck distribution percentages. Contrary to our expectations, we found that there were more pickups than SUVs at the Moores Mill site. We speculate that this unexpected result is due to the fact that during the day, the Moores Mill entrance ramp area serves as a truck route.

Figure 7-14
Truck Classifications by Site



Figures 7-15 and 7-16 break down frequencies of the truck types (i.e., pickups, SUVs and vans) by on-peak and off-peak time intervals, respectively.

Figure 7-15
Comparison of Truck Frequencies during Peak Hours by Site

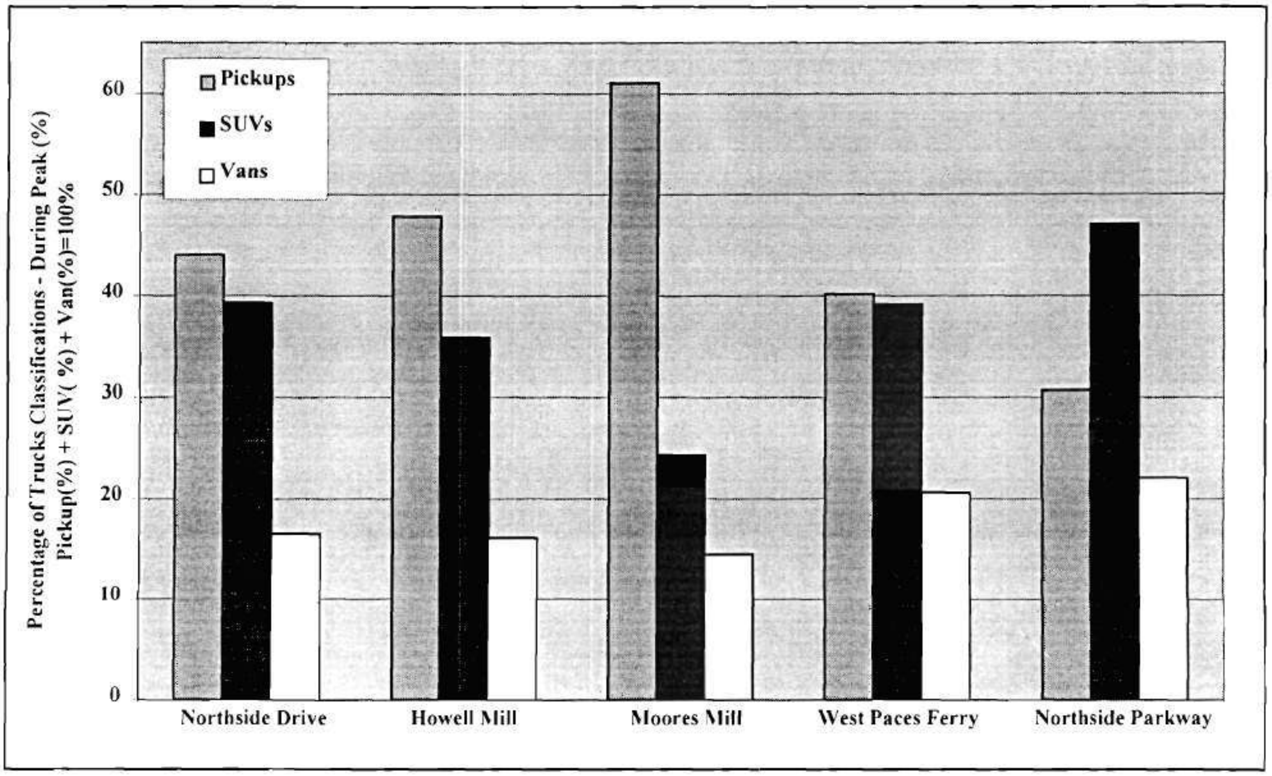
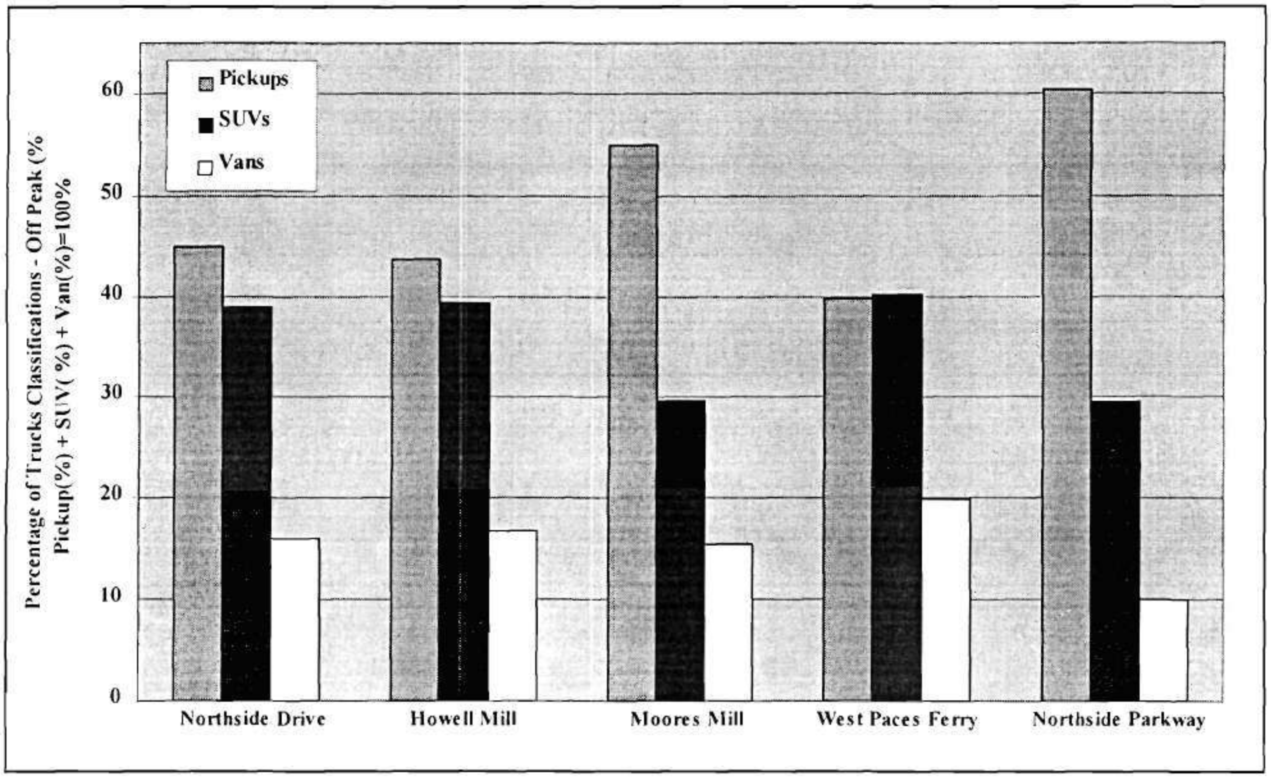


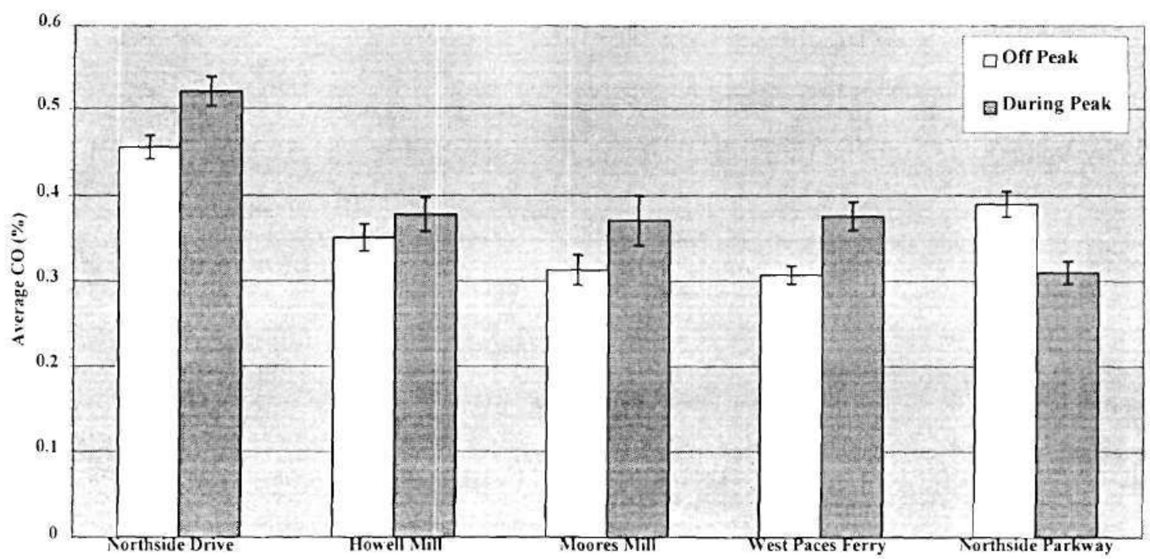
FIGURE 7-16
Comparison of Truck Frequencies during Off-Peak Hours by Site



7.2.5 Data Analysis for Emissions Measurements

Since the objective of this study was to analyze the effect of ramp meters on vehicle emissions along I-75 northbound, it was important to compare the off-peak emissions (i.e., when the ramp meters were off) with the on-peak emissions (i.e., when the ramp meters were on). Figure 7-17 illustrates that on-peak CO emissions were higher than off-peak emissions for all sites except Northside Parkway. We speculate that off-peak emissions are higher for Northside Parkway because the traffic along I-75 northbound during the peak is slower and more congested during the peak time. Therefore, off peak emissions are higher at Northside Parkway because vehicles have slower speeds during peak times and they move slowly during on-peak times while merging onto the interstate.

Figure 7-17
Average CO Emissions by Site and Time Interval



This hypothesis is supported by Figure 7-18, which illustrates that there is a larger discrepancy between peak and off-peak speeds at the Northside Parkway site than at the Howell Mill or West Paces Ferry sites.

Figure 7-18
Average Speed for Peak vs. Off-Peak Periods

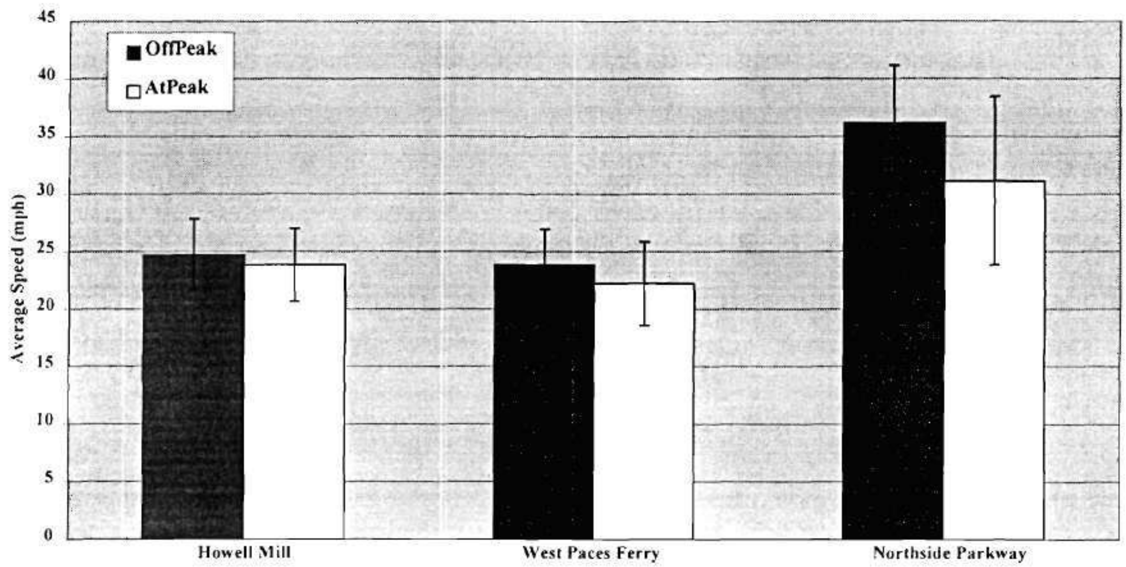
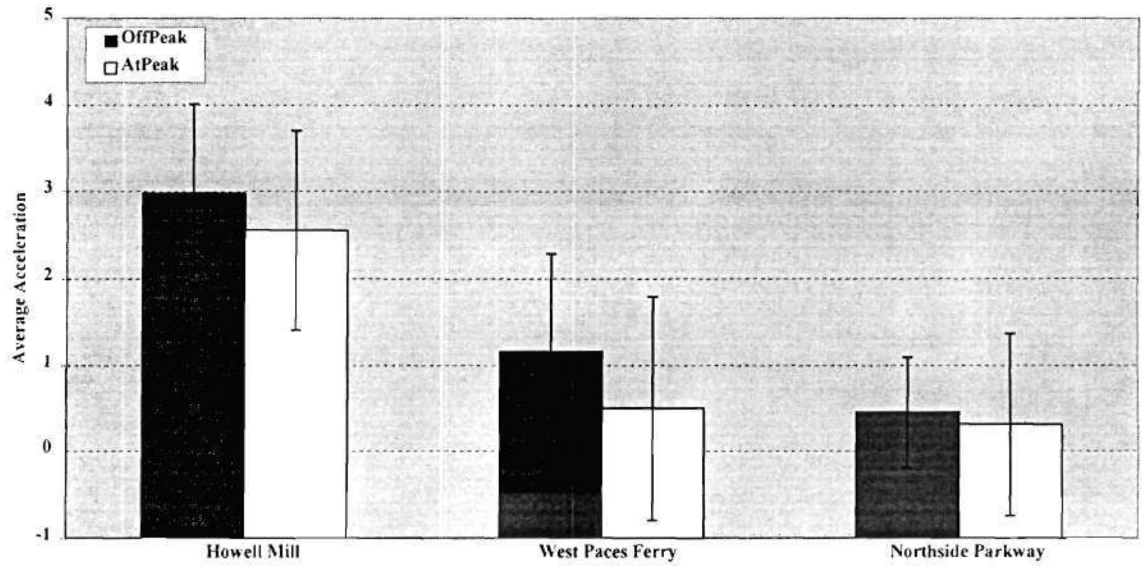


Figure 7-19 shows that at all three sites (Howell Mill, West Paces Ferry and Northside Parkway) the average off peak acceleration is higher than the average on-peak acceleration. This result is expected because traffic along I-75 northbound is slower during peak times than off peak times at all sites. Therefore, vehicles at all sites accelerate more slowly (at the remote sensor) while entering the interstate when the ramp meters are on.

Figure 7-19: Acceleration by Site and Time Interval



In summary, the research team found that the difference between vehicle emissions during off-peak times (i.e., before 3:30pm and after 6:30pm on weekdays and all weekend) and on-peak times (i.e., between 3:30pm and 6:30pm during weekdays) is dependent on five factors (cited in order of influence):

- age of vehicles
- fleet composition by vehicle type
- change of traffic patterns
- changes in fleet composition throughout the day
- changes in fleet composition from day to day

These influences are illustrated in the accompanying figures. Figure 7-20 illustrates that for all five sites, cars entering the highway have higher total emissions than trucks and those cars entering the highway during peak hours contribute the most to the total percentage of CO at each site. Conversely, trucks that enter the highway during peak times contribute the least to the overall amount of CO emitted. Note that this is on an aggregate basis and not that associated with an average vehicle. This surprising result is likely due to the relative ages of the cars and trucks that were captured by the remote sensing equipment. Figure 7-21 illustrates that trucks are newer than cars at each of the five sites.

Figure 7-20
Contribution to Average CO Emissions by Site and Vehicle Type

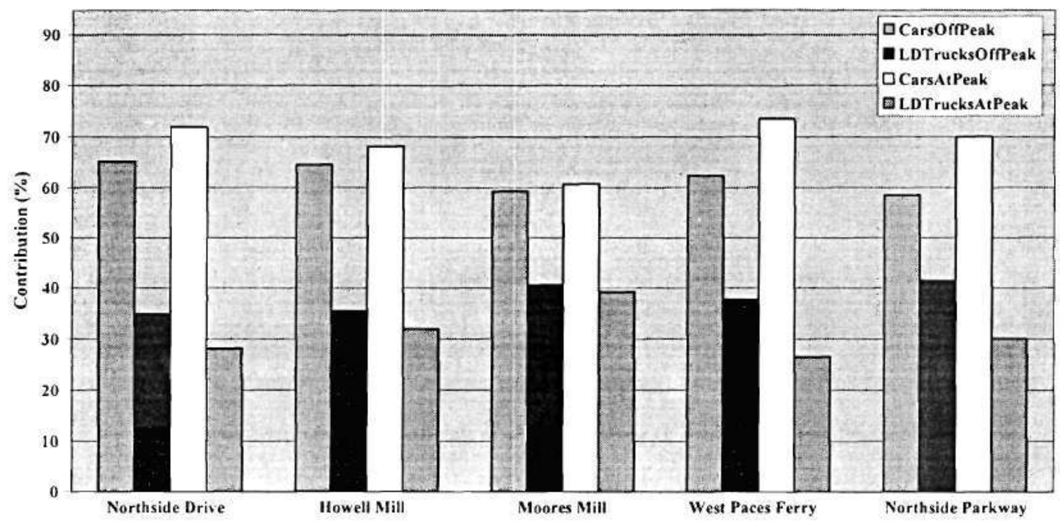
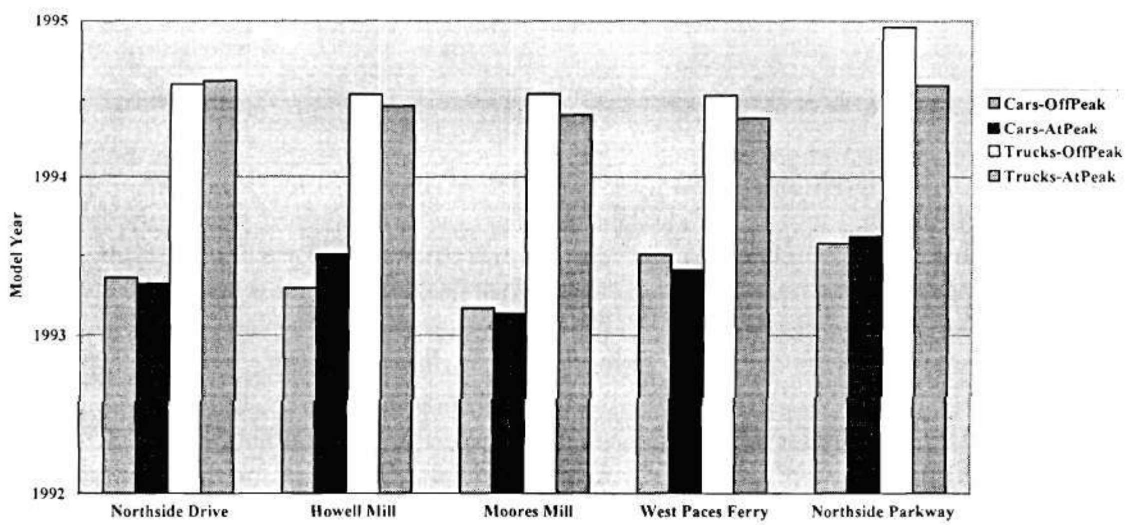
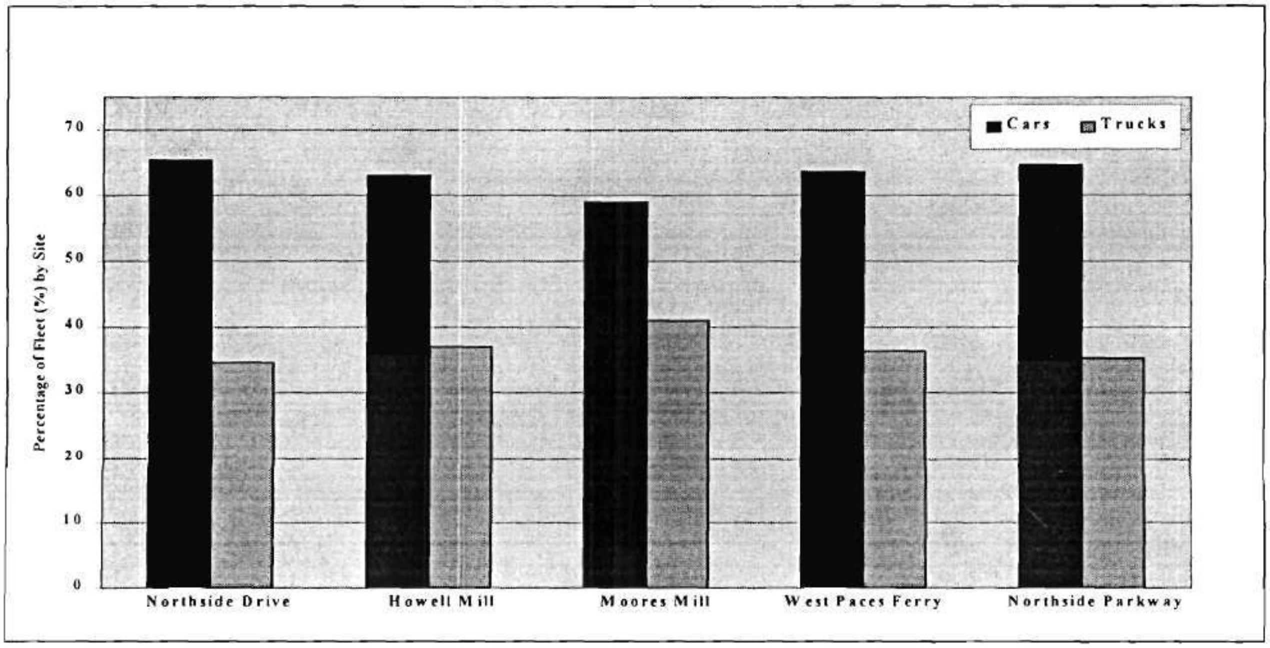


Figure 7-21
Average Model year of Vehicles by Site and Type



For the five sites, between 59% and 65 % of the emissions measurements collected were for cars. Figure 7-22 illustrates the distribution of measurements that for cars and trucks, respectively, at each site.

Figure 7-22
Distribution of Data Collection for Cars and Trucks by Site



7.3 Mainline Emissions Monitoring

In addition to the remote sensing measurements on the metered ramps, emissions measurements were conducted on the I-75 Mainline to evaluate in changes in emissions due to ramp metering. These measurements focused on two basic approaches to roadway measurements. These are the micrometeorological flux method and the Carbon Dioxide ratio method. In the former, high speed measurements of turbulence and Carbon Dioxide fluctuations are recorded to observe the correlation between concentration shifts and wind direction. This technique, known as eddy correlation can be used to determine the mass flux of Carbon Dioxide (total fuel consumption) from the roadway. Using ratios of other pollutants to Carbon Dioxide (e.g., HC/CO_2) measured independently (e.g., by remote sensing), absolute emissions rates can be determined. In the Carbon Dioxide ratio method, fuel consumption (i.e., average fleet fuel economy) is assumed to be known to within a relatively small uncertainty (less than 10%) and thus Carbon Dioxide flux can be calculated relatively accurately. By then rapidly measuring ratios of pollutants to Carbon Dioxide emissions rates for pollutants can be estimated. In practice, the two methods are complementary with the eddy correlation flux method being used to verify the results of the fuel consumption modeling and the ratio method determining the pollutant fluxes.

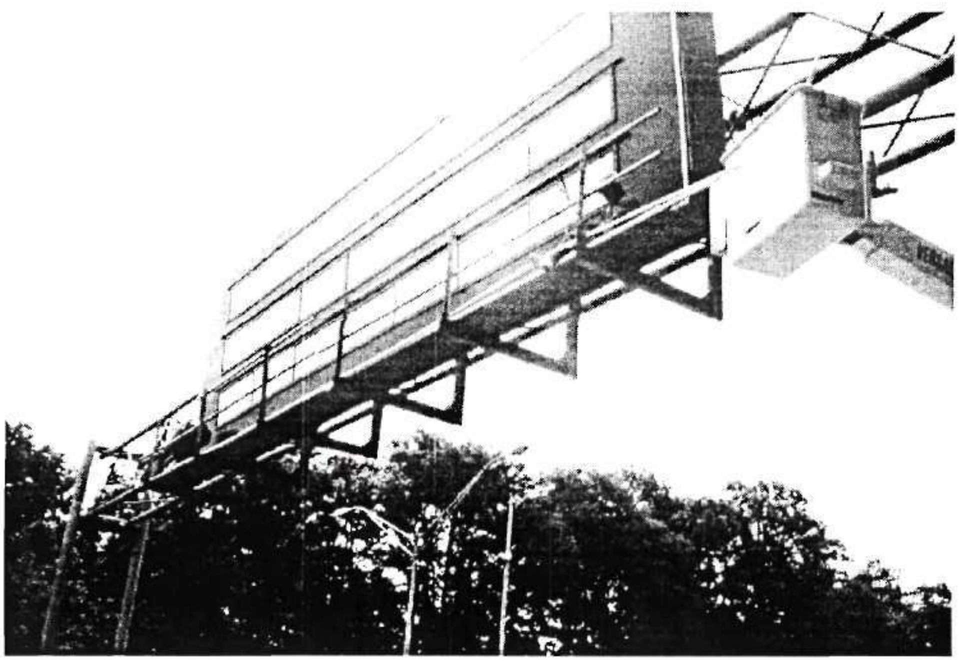
7.3.1 Measurement Sites

For this study, two independent sites were established. One site focused on measurements on the Southbound lanes while the second (primary) site focused on making measurements over the Northbound lanes of I-75.

7.3.1.1 Southbound Site

The southbound sampling site was located adjacent to the changeable message board between the Moores Mill and Howell Mill exits. Three high-speed sampling manifolds were installed on sign support structure for sampling across the southbound lanes. The manifold was constructed of 1" pipe that was connected to a blower. The first manifold location was between lane 5 and the emergency lane. A picture of the sampling location is shown in Figure 7-23. The center location was above lane 4 and the third manifold was located above lane 2.

Figure 7-23
GDOT Workers Install the Sampling Manifold at the Southbound Site

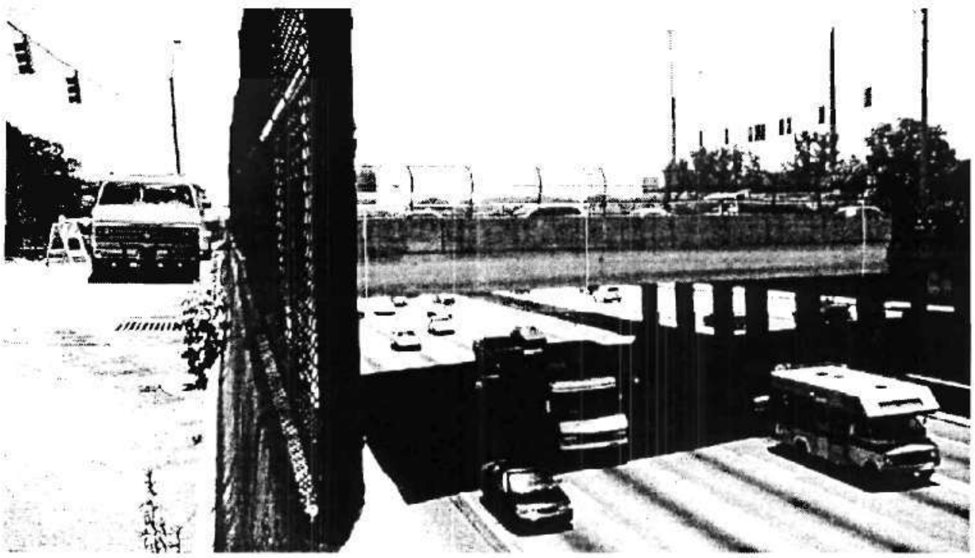


A three-axis sonic anemometer was installed on the sign support structure adjacent to the first sampling location. This system provides the high speed atmospheric turbulence measurements needed to evaluate the carbon dioxide flux. A 6'x6' climate controlled fiberglass instrument shelter was placed next to the vertical sign support structure to house the analytical instrumentation and the data collection systems. The shelter, sampling manifold and analytical instruments were installed at this location during the week of May 17th. Emission sampling began at this site on May 24th and continued to the end of July.

7.3.1.2 Northbound Site

The northbound sampling site was located on the Howell Mill Road bridge deck. The high-speed manifolds were installed in a manner that the sampling port entrance was below the bottom of the bridge-deck. The first manifold was located above the emergency lane, the center manifold was above lane 3 and the third manifold was about lane 1. A photograph of the sampling site is shown in Figure 7-24. Three sampling manifolds are located in the highlighted area. The van and sampling trailer are on the left-hand side of the picture. The analytical instruments and data acquisition systems were housed in a portable temperature controlled shelter that can be seen to the left of the photograph. Due to theft and vandalism concerns, the shelter was transported to the site during sampling days.

Figure 7-24
Howell Mill Sampling Site



7.3.2 Instrumentation

Both sites contained the same set of continuous air pollution instrumentation for the measurement of CO, CO_2 and NO_x. A sampling schematic is shown in Figure 7-25. The measurements available at each site are also summarized in Table 7-8 on the following page.

Figure 7-25
Instrument Schematic

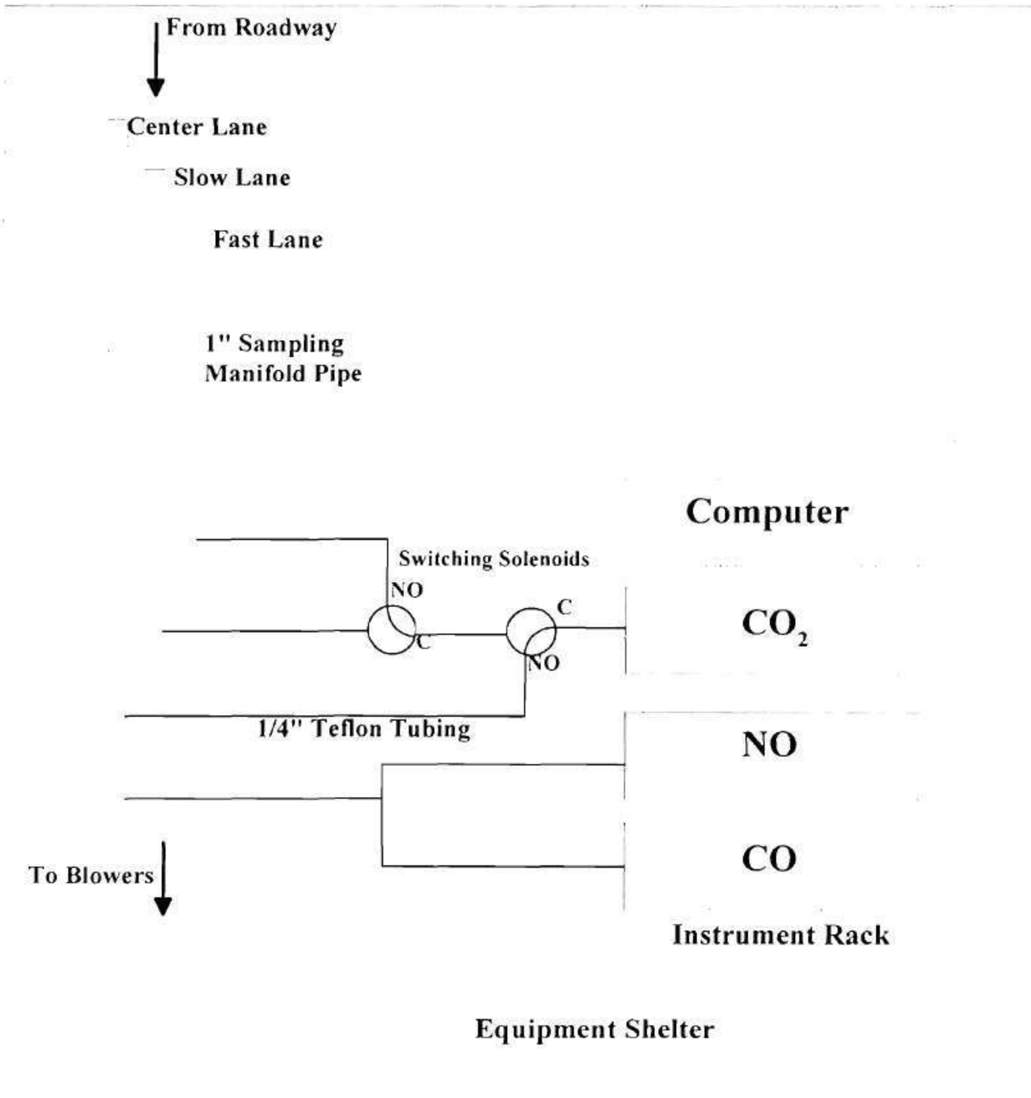


Table 7-8
Site Instrumentation

Table 7-8. Instruments Used at Each Site.		
Instrument	**Southbound**	**Northbound**
Carbon Monoxide	X	X
Nitric Oxide	X	X
Carbon Dioxide	X	X
Carbon Dioxide Flux	X	X
Three-axis sonic	X	
Speed/Acceleration		X
Vehicle Counts		X

Carbon Monoxide (CO) was measured by gas filter correlation with an infrared source and detector. The instrument is a TECO (Thermal Environmental Instruments, Inc, Franklin, MA) model 48 with a limit of detection of 0.10 ppm (parts per million) and a range of 0-10 ppm. Radiation from an IR source is chopped and passed through a rotating gas filter wheel alternating between CO and N2. The light passes through a narrow bandpass interference filter and enters a multiple optical pass cell (white cell) where absorption by the sample gas occurs.

Carbon dioxide (CO_2) was measured in each manifold very minute using a differential, non-dispersive, infrared (NDIR) instrument (Li-Cor, Inc., Lincoln, NE) using a solid-state detector filtered at 4.26 microns. The range of the instrument is 0-3000 ppm with an accuracy of 61 ppm. The Li-Cor instrument can sample CO_2 at a speed of 10Hz. This high sampling speed allows for the measurement of CO_2 flux. The CO_2 instrument was connected to a computer-controlled solenoid valve system so that CO_2 could be measured on all three manifolds sequentially.

Nitric Oxide (NO) was measured by ozone-chemiluminescence with a TECO (Thermal Environmental Instruments, Inc, Franklin, MA) Model 42s. The instrument has a range of 0-1000 ppb (parts per billion) and a minimum detection limit of 0.5 ppb.

The southbound location was equipped with a three-axis sonic anemometer (Applied Technologies, Inc., Longmont, CO) for measuring temperature and wind speed in three dimensions. Wind velocity is measured by transmitting and receiving sonic signals along a fixed (15 cm) path along each of the tree directions. An integrated microcomputer processes the data and calculates the wind velocity for each of the three axis. The measurement range of the instrument is 20 m/sec for wind speed with an accuracy of 0.03 m/sec. A picture of the sonic anemometer is shown in Figure 7-26. The sampling rate of the sonic anemometer was 10 Hz.

A photograph of the instrumentation in the portable shelter is given in Figure 7-27. From top to bottom, the instrumentation package consists of the Calibration System, Carbon Dioxide Measurement System, Nitrogen Oxide Measurement System, Carbon Monoxide Measurement System.

Figure 7-26
Three-Axis Sonic Anemometer at the Southbound Site

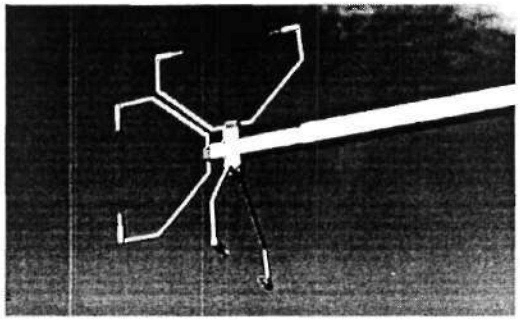
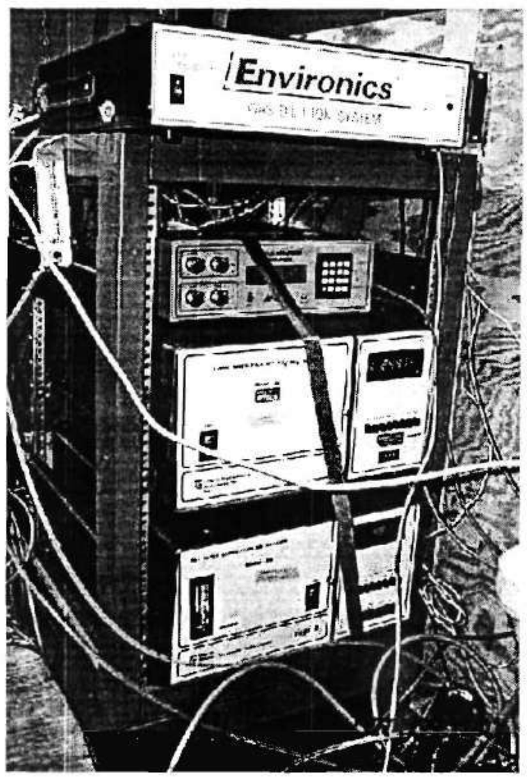


Figure 7-27
Instrumentation Package



The measurement site itself is illustrated in Figure 7-28 taken on the Howell Mill Road Northbound Entrance Ramp. Ambient measurements are taken in the can on the left. The remote sensing is conducted in the van further down the ramp.

Figure 7-28
Howell Mill Entrance Ramp Sampling

7.3.3 Measurement Results

Emissions at any one location are a function of traffic volume, fleet composition and levels of congestion. For interstate highways a sensitive parameter is the fraction of heavy-duty Diesels that strongly influence emissions of nitrogen oxides. Typical measurement results are illustrated in Figures 7-29 to 7-31. These figures illustrate the high degree of variability of emissions and the rapidity with which these emissions can change. Much, if not most, of the high frequency structure in the data is associated with the passage of high emission vehicles, especially medium and heavy-duty trucks through the sampling region. The more gradual shifts in emissions are clearly associated with changes in overall traffic volume with the overall highest emissions being present under congested conditions (e.g., 14:15 on 6/21). The primary objective of these measurements was to establish the impact of ramp metering on the mainline emissions, normalized for traffic volume and fleet composition. These widely varying emissions on the main line segments make quantification of the small (<5%) impacts on main line emissions predicted for ramp metering operations difficult and of limited accuracy. Based on the result of this sampling, the mean estimated influence of ramp metering is a 1% reduction in emissions.

This small reduction is, however, not statistically significant and to the limits of the accuracy of the measurements (+/- 8-10%) ramp metering has no discernable influence on the normalized mainline emissions at this location.

Figure 7-29
Emissions Measurements for 6/17/99

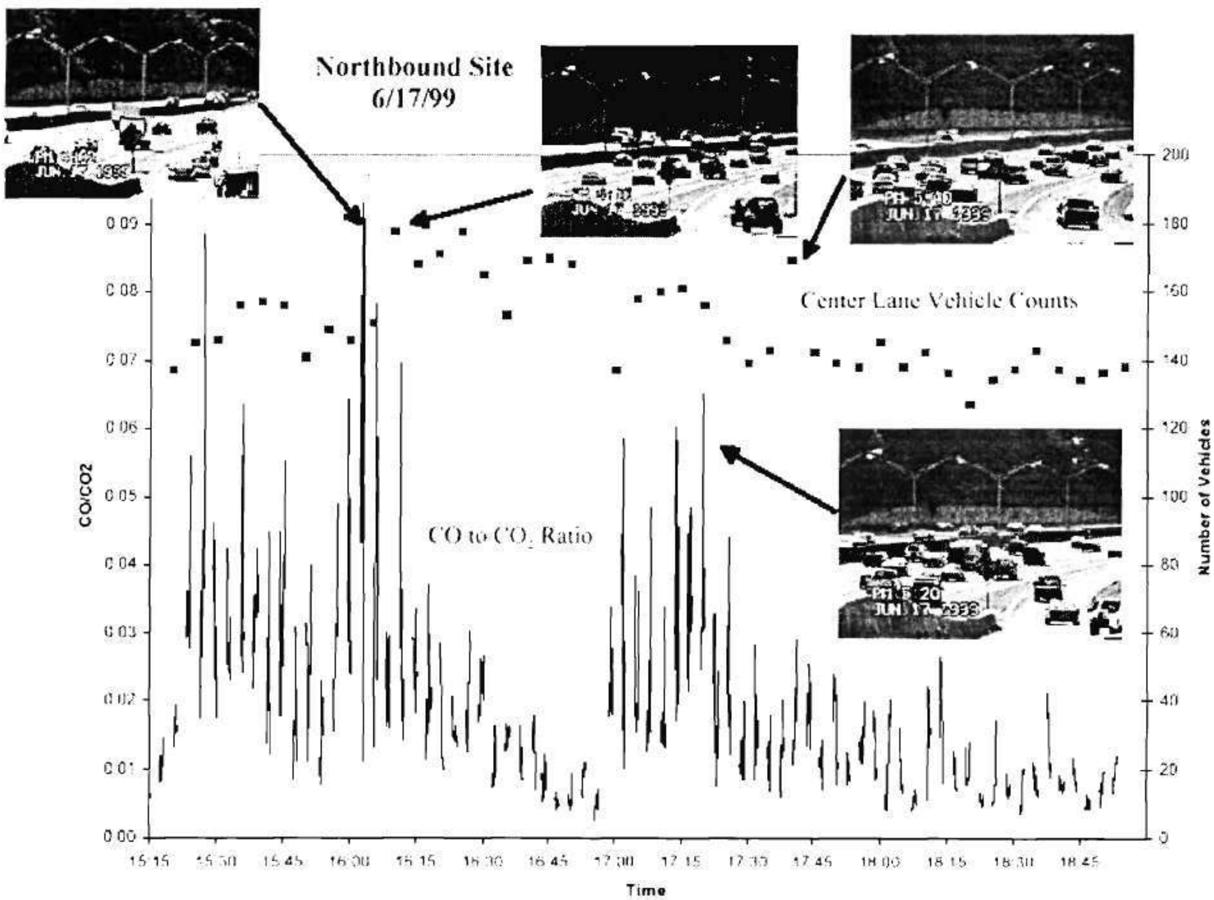


Figure 7-30
Emissions Measurements for 6/18/99

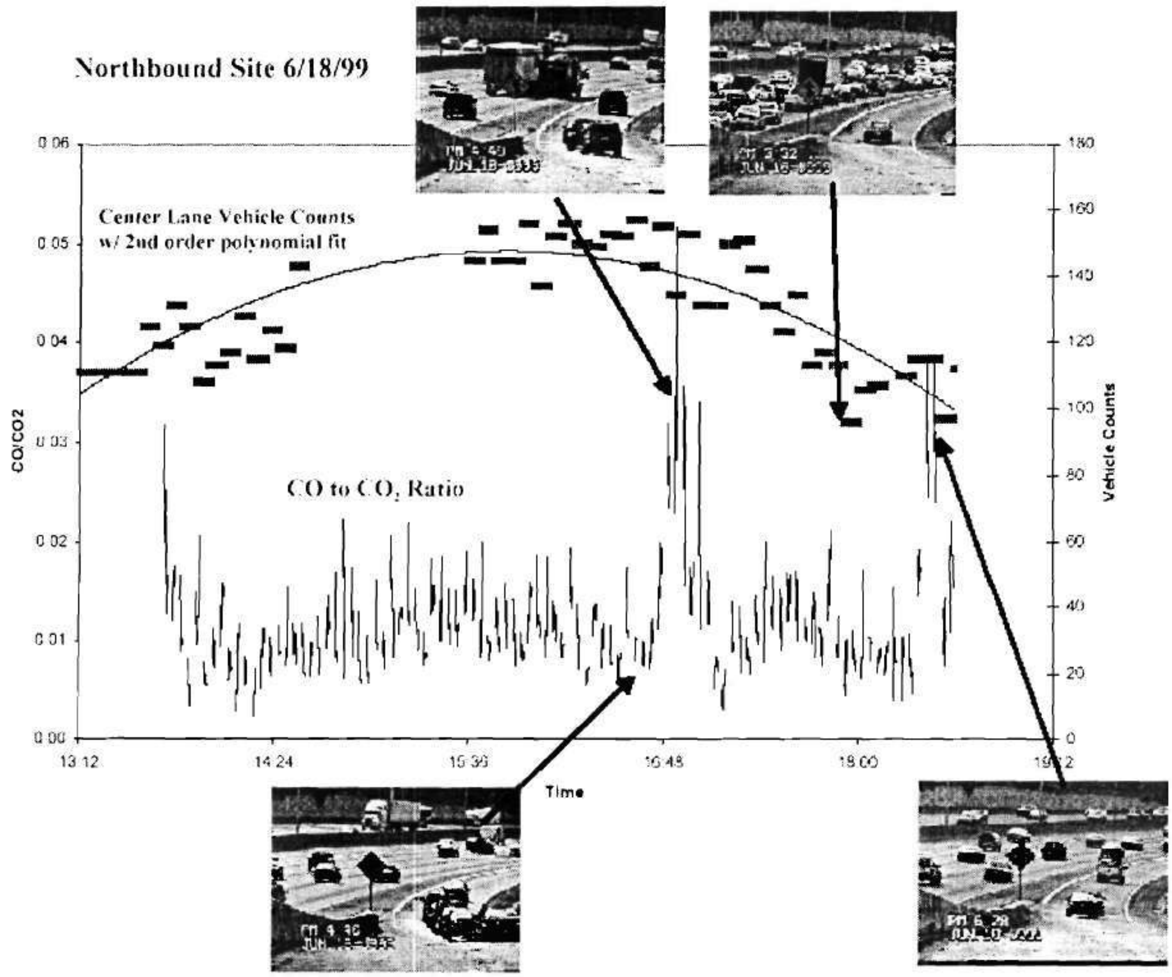
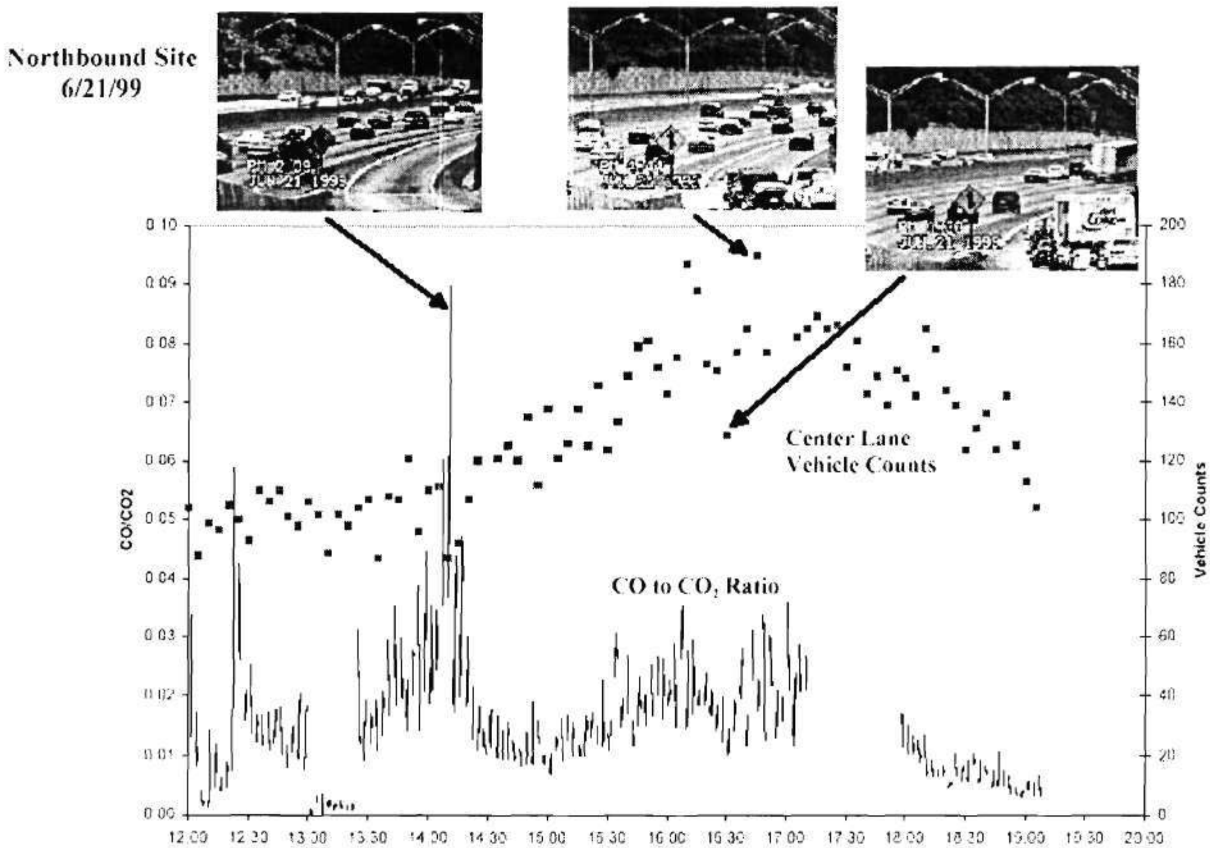


Figure 7-31
Emissions Measurements for 6/21/99



The analytical results do not preclude a small positive impact of ramp metering here or imply that ramp metering would not have a greater impact at some other location. This observation is, however, consistent with model predictions as to the magnitude of the overall emissions influence on main line emissions. As discussed earlier, however, there is a statistically significant increase in emissions for vehicles entering the highway during operation of the ramp meters that must also be considered in an overall evaluation of the emissions influence of ramp metering.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

Transportation agencies often implement ramp metering and other traffic flow improvement projects with the intent of improving air quality and reducing congestion. The Clean Air Act Amendments of 1990 and the Transportation Equity Act for the 21st Century encourage the use of traffic flow improvements, such as ramp metering, as a means to improve air quality because they mitigate traffic congestion. However, emissions from motor vehicles do not necessarily decrease in proportion to reductions in traffic congestion and vehicle delay. Numerous factors influence the level of vehicle emissions. Under some conditions, a tradeoff between travel speed and emissions can exist. In addition, a tradeoff between different pollutants (e.g. NOx and HC) can also exist. Research has demonstrated that emissions are a function of both the changes in hours of vehicle operation (i.e. average speed) as well as changes in vehicle modal operation (associated with speed/acceleration profile). The current version of the US Environmental Protection Agency emission rate model (MOBILE5b), which only directly accounts for average speed effects, may not predict accurate emission rates in certain applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). Hence, the emissions impacts that may result from a more widespread implementation of ramp meters in the Atlanta are unclear.

To date, modeling techniques have not been capable of capturing off-cycle conditions and, in turn, have been unable to accurately analyze the air quality impacts of many traffic management strategies, including ramp metering. This research has attempted to add to the understanding of the systems impacts of transportation control measures (TCMs), especially those that influence onroad vehicle operating modes. This was accomplished through the application of current modeling techniques and a new modal emissions modeling tool (the MEASURE Aggregate Modal Model) in the analysis of the Atlanta ramp metering system as a case study.

The research team collected vehicle activity and operating mode data from the Atlanta metered system for 18 days. More than 26,000 laser gun traces of onroad speed/acceleration activity were collected during this study. The laser gun data comprise more than 480+ hours of onroad operating data, approximately 75% of which were collected at ramps and 25% collected on mainline sections. To supplement the remote sensing data, and obtain information on operating characteristics in areas that could not be monitored by laser gun, more than 200 instrumented vehicle runs were performed on mainline sections and more than 275 instrumented vehicle runs were performed on ramps. Ramp meters were not operated on 4 of the 18 data collection days. Hence, the research provided the opportunity to compare operations under metered versus non-metered conditions. Detailed data collection methods were discussed in Chapter 4 and results from the field assessments of vehicle activity were presented in Chapter 5. The study has assembled the largest operating mode profile database for a metered ramp system.

8.1 Observed Ramp Metering Effects

Researchers applied the MOBILE5a average speed emission rates and the MEASURE Aggregate Modal Model emission rates (discussed in Chapter 3) to the vehicle activity and operating mode conditions observed in the field. The assessment indicated that ramp meter operation on the I-75 study corridor had a potentially detrimental effect on vehicle emissions. Both the MOBILE5b and MEASURE Aggregate Modal Model results predicted an increase in NOx emissions under metered conditions. The MEASURE Aggregate Modal Model predicted larger emissions increases for all pollutants than did MOBILE5a.

Under volume-controlled conditions, predicted HC mass emissions estimates for all four onramps rose from 40 to 46% under metered conditions. The opposite trend at ramps was apparent for estimated NOx emissions. While the predicted Northside drive ramp emissions dropped by only a few percent under metered conditions, NOx reductions at the other ramps ranged from 12 to 22% under metered conditions.

While the onramp emissions estimates were important, the mainline emissions dominated the overall system evaluation. The estimated HC emissions analysis for the mainline section showed a 2% decrease in mass emissions under metered conditions. Total predicted system-wide HC emissions were lower by about 1% on a typical day when ramp meters were in operation, given the significant predicted increase in emissions at the ramps. Using measured vehicle activity and the MEASURE Aggregate Modal Model, researchers predicted an increase in mainline NOx emissions of approximately 4% under metered conditions. System wide NOx emissions were also predicted to increase by approximately 4%, because the ramp emissions decreases were insignificant compared to the mainline emissions increase.

It is important to consider that these conclusions apply only to the study corridor under the conditions normally observed during the field study. Extrapolation of these findings to other areas should only be preformed within the context of this study. The research indicated that ramp metering in the study corridor is not recommended, due to the fact that little travel time benefit is realized (a 2mph increase in average speed) and there is a modeled NOx emissions increase. This is not to say that the same conclusions would be reached for every potential ramp-metered corridor. Indeed, under certain congested traffic conditions, ramp metering can delay the on set of forced flow conditions and greatly improve travel time on a metered corridor. Because the study area never entered forced flow conditions, researchers undertook a series of CORSIM simulation analyses to provide insight into how the metering system would effect emissions under conditions that were never observed in the field.

8.2 Simulated Ramp Metering Effects

Analyzing the impacts of potential forced flow conditions was accomplished with the field dataset through the application of CORSIM simulation modeling tools. The data collected as part of this research was used to calibrate a CORSIM traffic simulation model, for use in simulating the effect of ramp metering on increased traffic volumes. The outputs from simulation runs were then used to assess the potential changes in modal activity and emissions under traffic conditions not observed during the data collection process. First, the research team simulated the existing corridor under observed conditions. The research team then examined: 1) the potential effects of high traffic flow conditions, as might occur just prior to forced flow breakdown; and 2) the potential effects of a lane-closure, where simulated forced flow conditions were achieved. Performing these analyses allowed for the assessment of the ramp metering system under a wider range of traffic conditions and provided a more complete understanding of the air quality impacts of ramp metering on the corridor.

8.2.1 Simulation of Observed Conditions

Emissions predictions from field data indicated between a 30 and 46% increase in ramp HC emissions, versus simulation run predictions of a net average increase in ramp HC emissions of 50%. Emissions predictions from field data indicated between a 2% to 22% decrease in ramp NOx emissions, depending on the onramp in question, versus simulation predictions of a net average increase in NOx ramp emissions of 21%. The research team noted significant differences between observed and simulated average speed conditions on metered and non-metered ramps. In the simulation, ramp speeds were predicted to drop from 44 mph to 8 mph under metered conditions. However, observed ramp speeds only dropped from 41 mph to 32 mph. Acceleration distributions also differed significantly as illustrated in the speed/acceleration plots. As discussed in Chapter 6, the research team believes that the discrepancy results from the simulation model's treatment of vehicles transferring between the arterial network and freeway network modules (at interface nodes) under congested conditions. Given the field findings, simulation model performance for ramps requires significant improvement.

Field observations yielded a predicted 2% decrease in mainline freeway HC emissions and an estimated 4% increase in mainline freeway NOx emissions. However, simulation results predicted much larger percentage increase in both HC and NOx mainline freeway emissions. Simulations indicated that a nearly 7% increase would result in both HC and NOx emissions for the freeway mainlines. Field observations recorded higher speed activity and more hard acceleration conditions under all ranges of speeds that lead to higher emissions in the MEASURE Aggregate Modal Model regime. The difference between emissions estimates arise predominantly from the difference in predicted starting points and changes in average speeds, and to some extent from differences in percentage of operations under higher power demand conditions (inertial power surrogate values). Again, the simulation models require improvement for predicting the high-speed activities that were observed on the freeway under current traffic conditions.

8.2.2 Simulation of High-Flow Conditions

The high-flow simulation exercises corroborated independent research efforts that have historically demonstrated that ramp metering has a potentially significant impact on mainline average freeway speeds under heavy flow conditions (roughly 10mph in this case). With ramp metering, mainline freeway hours of vehicle activity dropped by nearly 20% under high-flow conditions, compared to a drop of only 8% under observed flow conditions. This occurred while ramp delay and arterial congestion contributions remained constant. Hence, as expected, ramp metering provides greater mainline freeway time savings under heavier traffic flow conditions. The basic problem is that under metered conditions gram/second emission rates increased at a greater rate than the rate of travel times decline. Thus, high volume conditions lead to potentially higher mass emissions for the metered scenarios than observed flow conditions. In this case, the net emissions increase from metering rose from 33% to 45% for NOx and from

37% to 39% for HC when moving to higher flow conditions. Hence, emissions impacts were even worse under high-flow conditions than under observed conditions.

8.2.3 Simulation of Lane-Closure Conditions

The lane-closure simulations also supported previous research efforts demonstrating that ramp metering has a potentially significant impact on mainline average freeway speeds. Simulations of observed peak-hour flows indicated that metering would yield a small increase in average freeway speeds; from 53 mph to 55 mph. However, under the lane-closure simulations, metering was predicted to increase average freeway speeds from 39 mph to 45 mph. Ramp metering was predicted to reduce mainline freeway travel times by 6% for non-lane-closure conditions and by 13% under lane-closure conditions, indicating that ramp metering is even more effective at reducing travel delay under incident conditions.

As with the previous simulations for observed flow and high volume flow conditions, metering under peak-hour and peak-hour lane-closure conditions are predicted to lead to higher emissions. Metering under peak-hour conditions lead to a predicted 4% increase in HC and NOx emissions. These increases come with a relatively small increase in average speeds (less than 3 mph). Metering under peak-hour lane-closure conditions was predicted to increase HC by 4% and NOx by 6% compared to non-metered lane-closure conditions. The smaller predicted increase in mainline and ramp emissions under lane-closure conditions comes with much larger mainline freeway travel time savings (nearly 50 seconds per vehicle).

The simulation scenarios indicated that the system would experience very large increases in travel times and emissions on local roads under lane closure conditions. The increases in arterial travel times may be more than enough to offset travel time benefits gained on mainline freeway segments. The impact of ramp metering on the local arterial segments appears from simulation results to be a critical factor in ramp metering system evaluation. In designing ramp meter solutions, engineers and planners should ensure that ramp queues do not spill back onto arterials.

As outlined in Chapter 6, there is a great deal of uncertainty associated with the simulation predictions on ramp speeds and mainline high-speed operations. The differences between simulated and observed traffic data under normal operating conditions indicate that simulated flows for high-flow conditions are likely to underestimate the maximum speeds and acceleration rates on the mainline. Hence, real world emissions under metered conditions for heavy congestion and lane-closures may be higher than predicted by the simulation outputs. Thus, although the percentage emissions increases that result from metering may be somewhat lower in the real world than were simulated, the net magnitude of the predicted change may be higher. Nevertheless, great care must be taken in attempting to extrapolate these simulation results to other corridors and operating conditions. There are no field observations under high-flow or lane-closure simulation conditions to which researchers can compare the simulation results. Moreover, the simulation models require improvement.

8.3 Results from Field Emissions Measurement

The peak-period and off-peak vehicle fleet observed in the study corridor changed significantly as a function of time of day. The fleet was slightly older, and more trucks and sport-utility vehicles were observed in off-peak periods. Based upon vehicle registration data, the evening peak period fleet appears to be composed primarily of commuters that are local residents (based upon the census block group of vehicle registration). In performing all work, the field emissions measurement team was required to explicitly account for the changes in vehicle subfleet characteristics as a function of time of day (normalizing for fleet composition) in drawing comparative emissions conclusions.

The remote sensing studies indicated that metered ramps yielded higher emission rates near the stopline under metered conditions for CO at 4 of 5 locations, for NOx at 3 of 5 locations, and for HC at 4 of 5 locations. This is not terribly surprising, as the instantaneous load on the engines under the hard acceleration conditions can lead to large increases in localized emissions. However, the measured results do not infer that emissions are higher for the entire ramp trip under metered conditions (emissions were measured near the point of maximum acceleration). Interestingly, the onramp location that consistently did not result in an emissions increase near the stopline was Northside Drive, a cloverleaf entrance ramp. The conditions under metered and non-metered conditions simply did not differ as greatly at this location because the tight cloverleaf requires significantly slower operating speeds under non-metered conditions (which are closer in form to metered conditions that at other ramps).

The Air Quality Laboratory field team installed sampling equipment above the roadway at two locations along the study corridor (one northbound and one southbound location). Given the physical nature of the traffic corridor, the vertical flux study examined the vertical migration of vehicle emissions moving from the roadway. The study concluded that measured emissions above the roadway are highly variable, and are heavily influenced by the presence of heavy-duty trucks. The impact of trucks on emissions is so pronounced that the pollutant concentration spikes can be observed directly in the data and linked to the video image of the truck's passage. Unfortunately, the field study could not determine a statistically significant difference in emissions flux on the corridor under metered and non-metered conditions. The modeled emission increase for HC was only 1% and for NOx was only 4%, both of which are well within the confidence bounds of the emissions measurements. Hence, no conclusions could be drawn regarding a measured emissions impact of ramp metering.

The field emissions team collected vertical flux emissions data on more days and over a longer data collection period than did the vehicle activity data collection team. On a number of occasions, the emissions measurement team observed traffic flow breakdown conditions (most likely due to an incident on the corridor), whereas vehicle activity data collectors never observed such conditions. Under these conditions, field monitoring did detect a statistically significant reduction in vehicle emissions from the corridor under forced flow conditions. These observations support the simulated results for breakdown conditions, which also predicted a reduction in mass emissions from the facility under forced flow conditions.

8.4 Guidelines for Optimizing the Air Quality Benefits of Metered Systems

The research results confirm previous ramp meter findings reported in the literature. First, and foremost, transportation planners and engineers should not install and operate ramp meter systems on corridors that will not significantly benefit from reduced mainline congestion. The emissions predictions under metered conditions were higher than the emissions from the comparable non-metered system for those conditions observed in the field and simulated. The emissions increase is the largest when the ramps are metered to provide a small increase in mainline flow speeds (e.g. under good level of service traffic flow conditions where metering increases speeds from 62 to 63 mph). The emissions increase (say between 1% and 4% for the 4-mile corridor) comes with reduced travel times of less than 5 seconds per vehicle. Under simulated conditions, the predicted emissions increases were larger (approximately 7%), but came at a slightly larger predicted travel time savings of approximately 25 seconds per vehicle. Given the field findings, the metered system currently in place on this I-75 Northbound section should probably be operated only when an incident, or other non-recurrent event, causes congestion problems on the corridor.

Simulation modeling predicted emissions changes resulting from operational changes on the ramps, mainline freeways, and the arterials. Under simulated high-flow conditions, the predicted NOx emissions increases associated with ramp metering were larger (in both mass emissions and percentage increase) than were predicted for the lower traffic flow conditions. HC emissions increases were roughly the same under simulated observed flow and high-flow conditions. However, these increases came with much larger increases in mainline freeway travel speeds. Metering under lower flow conditions was estimated to save approximately 25 seconds per freeway vehicle trip, but metering under high-flow conditions was estimated to save 82 seconds per freeway vehicle trip.

Although the simulation models do require significant improvement, the field and simulation results still indicate that analysts should perform detailed simulations before implementing metering systems. Simulation models can provide accurate volume estimates, although the speed and acceleration operating profiles are not accurate. Hence, the research team recommends coupling ramp metering simulation results with measured speed/acceleration profiles collected from existing systems (until the simulation models are improved). Meters will clearly provide mainline freeway congestion reduction and increased travel speed benefits. However, analysts should first ensure that implementation of the metering program will not significantly adversely affect traffic conditions on local arterials. Adverse conditions on arterials appear to be capable of more than offsetting mainline time savings. In the simulated observed flow scenario, the predicted 180 vehicle-hour benefit on mainlines was offset by a 100 vehicle-hour increase on ramps and 770 hour increase on arterials. In the simulated high-flow scenario, the predicted 620 vehicle-hour benefit on mainlines was offset by a 100 vehicle-hour increase on ramps and 770 hour increase on arterials. In both scenarios, ramp metering would have provided a system wide travel time reduction, had arterial travel times not increased. It is important to ensure that ramp queues do not spill back onto the local arterials.

Even when arterial operations are reasonably isolated from adverse effects of ramp metering (through proper ramp and signal timing design), it is still reasonable to expect that the emissions from the ramps and mainline freeway segments will increase under metering. Simulation results indicated that metering would increase ramp and arterial NOx and HC emissions (Tables 6-5 and 6-6, assuming zero arterials impact). NOx and HC emissions were both predicted to increase by approximately 7% under observed flow conditions when metering is implemented. NOx and HC emissions were predicted to increase by 20% and 11% respectively under high-flow conditions when metering is implemented. Given the travel time savings that result from metering under high-flow, lane-closure, or other conditions that lead to forced flow conditions, regions may want to trade-off the increased emissions for the travel time savings.

Study results indicate that ramp metering should not be implemented on ramps with steep uphill grades and/or short acceleration zones for gaining free flow traffic speeds. The hard acceleration events on short uphill ramps exacerbate emissions. Ramp metering strategies may benefit significantly from new and innovative design strategies. Roadway designs that allow for the slowing of vehicle activity and dispersing of platoons in the ramp zone, without requiring vehicles to come to a complete stop, may provide significant benefit in ramp-related emissions reductions. Such strategies should be the subject of ongoing research efforts.

8.5 Regional Context of Ramp Metering and Air Quality

The emissions differences for HC or NOx under metered versus non-metered conditions must be evaluated within a regional context. The daily NOx emissions budget for the Atlanta Region is approximately 245 tons per day (ARC, 1999). Therefore the estimated emissions increase due to ramp metering on this portion of the I-75 corridor accounts for less than 0.005 percent of the daily regional budget. This is for a small, four-ramp system. As metered systems increase in size, the relative impact will also increase. Nonetheless, it is apparent that even an extensive ramp metering system would not result in a large emissions change when compared to the regional budget. It is therefore important to keep in mind the current local emissions issues when evaluating the impacts of ramp metering and assessing the traffic congestion and operations tradeoffs in light of these emissions impacts.

8.6 Final Word

One of the most important findings of the study is that two assertions in conventional wisdom associated with the emissions impacts of ramp meter systems may not be correct. Some policy analysts have argued in the literature that ramp meter approaches will universally reduce vehicle emissions by reducing congestion levels. Other policy analysts have argued that because emissions from the ramps increase significantly when meters are in operation, that ramp meters are likely to increase system emissions. Neither of these positions appears to be correct:

- First, the field results and simulation modeling indicate that the emissions from the Atlanta I-75 system are not likely to decrease when meters are in operation for any of the operational scenarios examined. Were congestion levels to increase to extreme levels, metering may decrease emissions. However, the field team never observed such operating conditions in this corridor.

- The second position, that emissions increases on ramps are so great as to eliminate the emissions benefits on the mainline segments, also does not appear to be correct for this corridor. While research indicates that ramp emission rates increase significantly, the net impact of increased ramp emissions is small because the ramps contribute only a small fraction of the system emissions. The controlling factor was the predicted increase in mainline emissions (the dominant contributor to total system emissions) when the meters were in operation. Thus, the emissions increase on the system was almost entirely due to the increase in speeds and loads on the mainline freeway segments when the meters were in operation.

The findings of this research are limited to the scope of the case study, providing an assessment of the potential emission impacts associated with Atlanta's existing metered corridor. This research has provided two critical elements that will allow for more effective ramp metering and air quality research in the future. First, this research provided a basic analytical framework (data collection and analytical methods) that can be applied in future studies. Second, the research established a comprehensive dataset for ongoing analysis.

The research results indicate that ramp metering systems should not be operated when freeways are running at high levels of service. As freeway conditions approach flow breakdown, regions need to decide whether the tradeoff between increased emissions and reduced travel time warrants the implementation of the metering strategies. Simulation modeling tools and modal emissions models can help with this decision, even though there is still a great deal of uncertainty in both the simulation and emission rate model outputs used in such analyses. To provide a more complete picture of the potential air quality impacts of ramp metering, further fundamental research is required. As the modeling tools continue to evolve, the new modeling routines can be applied to the data collected for this project so that specific timing strategies can be properly evaluated.

The region needs to decide whether the reduced travel times from metering are worth potential increases in emissions. If so, the region will need to identify alternative means of reducing the emissions that may result from improved traffic flows on the freeway corridor. New freeway corridors that are likely to be metered may yield a small relative increase in the overall regional emissions inventory. Given the potential travel time savings of highway users (assuming arterial degradation can be avoided), it seems reasonable to pursue such alternatives to compensate for any predicted emissions increase. Ramp metering has been, and will likely continue to be, a popular cost-effective traffic management tool with a high potential for improving freeway traffic flow. Ultimately the decisions to implement a ramp metering system will be a function of the specific traffic operations and air quality issues associated with the area under consideration. Given the projected emissions increases, optimizing the tradeoff between time savings and increased emissions will likely be next order of business in modeling the detailed impacts of ramp meters.

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APPENDIX A
POLLUTANT CHARACTERISTICS

Oxides of Nitrogen

NOx compounds, such NO, NO_2, and NO_3 are the result of the combustion process. Nitrogen is often bound to combustion fuels and the ambient air is composed of 79 percent nitrogen, therefore NOx compounds are an unavoidable result of the combustion process. Details of why this occurs are provided in the discussion of combustion in the following section.

Brownish in color with a pungent smell, NO_2 is one of the primary contributors to visible urban haze and brown smog. Relative to other criteria pollutants NO_2 is not considered a health risk, although in high concentrations it can result in damage to cells in the respiratory tract (SCAQMD, 1997). Currently there is not a single area in the US that is in violation of the NO_2 standard (USEPA, 1999). Ninety percent of the NOx compounds resulting from combustion are in the form of nitric oxide (NO). In the presence of sunlight and other combustion byproducts such as volatile organic compounds (VOCs), NO will contribute to the formation of tropospheric ozone. That is, NO and other NOx compounds are not serious pollution problems in and of themselves, but are precursors to more hazardous ozone formation. It is estimated that approximately 50-70 percent of NOx emissions result from motor vehicles, with the residual resulting from electric utilities and industrial boilers.

Oxides of Sulfur

Formed by the oxidation of elemental sulfur in fuel, SOx is a colorless gas with a distinct odor, and is also the result of combustion. SOx is not a serious automobile pollutant since sulfur levels in gasoline and diesel fuels are highly regulated. The primary sources of SOx pollution are from industry and power plants that use coal with a high content of sulfur.

Carbon Monoxide

A colorless and odorless gas, CO is the result of incomplete combustion of hydrocarbons. It is primarily a localized pollution concern or what is referred to as a 'hot spot' problem. This is due to the fact that it disperses well and will not typically have time to accumulate at ground level. An exception to this is at high elevation or during cool weather conditions that occur during winter months. Almost all CO air pollution (i.e. 90 percent), is the result of automobile tailpipe emissions (USEPA, 1997).

When CO does accumulate in high concentrations it is a deadly pollutant. When inhaled it interferes with the oxygen carrying capacity of the blood, which results in drowsiness, headaches, and impairment. At high concentrations CO poisoning can be fatal, although such conditions do not typically occur in ambient air (SCAQMD, 1997).

Particulate Matter

Solid or liquid particles composed of smoke, ash, pollen, or chemical droplets, particulate matter becomes an air pollutant when it is small enough to stay suspended for prolonged periods. Particulate matter can be a hazard by itself or act as a carrier for other toxic air contaminants. It also contributes significantly to visibility degradation.

Combustion is the primary source of direct particulate matter, producing particles that range from .01 to 10 microns in diameter. Automobile and other on-road combustion accounts for approximately one quarter of all direct particulate matter with the remainder coming from stationary sources (USEPA, 1997). Particulate matter can also result from fugitive sources such as agricultural activity, construction sites, road dust, and naturally occurring wind erosion.

As can be seen in Table 2-1, there are two standards for particulate matter, one for particles less than 10 microns in diameter (PM_{10}) and one for particles less than 2.5 microns in diameter ($PM_{2.5}$). Large particles can cause scaring of lung tissue and aggravate respiratory and heart problems, while fine particles less than 2.5 microns can enter the blood stream and lead to more serious health problems and premature death. As with most air pollution, health problems are accentuated for the young, elderly, and those with respiratory problems such as asthma (Wilson and Suh, 1997).

Lead

Added to automobile fuel as an anti-knocking compound and performance-enhancing agent, lead is carried on combustion particulates. Lead is a toxic heavy metal that, when air born, can enter the lungs and bloodstream and result in brain and nervous system damage. This is particularly a problem for developing individuals. Starting in 1978, lead additives to fuel were phased out and are not allowed in gasoline. As a result, lead air pollution from automobile sources, has been virtually eliminated.

Ozone

Ozone (O_3) is a serious air pollution problem when it accumulates at the ground level. Unlike stratospheric O_3, which provides protection from ultra-violet rays from the sun, ground level or tropospheric O_3, can damage lung tissue and reduce lung capacity. Tropospheric O_3 is the primary component of urban smog. When exposed to O_3 for six to seven hours, even at relatively low concentrations lung function is significantly reduced in normal, healthy individuals during moderate exercise. The current air quality standard for O_3 is 0.12 ppm one-hour maximum concentration over a twenty-four hour period. Many health studies have indicated that negative effect of O_3 can occur at lower concentration if exposure is for an extended period of time (USEPA, 1996). In light of this the USEPA has recommended an additional O_3 standard of 0.08 ppm maximum 8-hour concentration over a twenty-four hour period (62 CFR 138). This new standard promulgated in 1997 is currently being challenged in court and was not in effect at the time of this research.

Unlike the other five criteria pollutants, O_3 is not emitted directly into the air by specific sources. It is formed when NOx compounds and VOCs react with sunlight in the lower layers of the atmosphere. These precursors to O_3 can be the product of numerous sources. As discussed NOx compounds are the result of combustion. VOCs in the form of hydrocarbons can also be the result of combustion as well as other industrial processes and natural sources. Often these precursors will be emitted in one area and transported in the atmosphere for miles before reacting to form O_3. As a result, high O_3 concentrations can occur over areas that are distant from the precursor source and in areas low in air pollution emissions.

Volatile Organic Compounds

Volatile Organic Compounds (VOCs) are reactive hydrocarbons that contribute to O_3 formation. VOCs include many chemical species of hydrocarbons, but do not include methane and other non-reactive compounds. Some of the more reactive and problematic VOCs include ethylene, acetylene, ethane, propylene, and even toxic compounds such as benzene. There are numerous sources of VOCs including solvents and other industrial processes, waste disposal, evaporation and incomplete combustion of motor vehicle fuels, and natural sources. In some areas, forest canopies can contribute up to 50 percent of the VOC emissions in the form of terpenes (from pines) and isoprenes (from various broad-leaf plants).

Ozone forms when VOCs mix in the lower layers of the atmosphere with NOx compounds in the presence of sunlight. The resulting concentration of O_3 is a complex function of weather conditions and precursor emissions. As a result, ozone pollution levels are very difficult to predict and control. Ozone pollution is a problem that is wide reaching and difficult to control. Although VOCs are not a criteria pollutant, they are an important player in the formation of ozone. It is therefore just as important to monitor and control VOC emissions as it is other criteria pollutants. This is particularly important in urban areas where motor vehicles can contribute more than 30 percent of the total VOC emissions.

APPENDIX B

MOBILE5b Control File

```
5       PROMPT
 1999 (Jan. 2000), Atlanta (03naa-2.txt)(ramps.txt)
1       TAMFLG
1       SPDFLG
1       VMFLAG
3       MYMRFG
2       NEWFLG
6       IMFLAG - Enter I/M control flag record.
1       ALHFLG
5       ATPFLG - ATP and Pressure, no Purge
2       RLFLAG
2       LOCFLG - LAP record appears once, in One-Time data section.
1       TEMFLG
4       OUTFMT - 80-column
4       PRTFLG - Print exhaust HC, CO and NOx results.
1       IDLFLG
3       NMHFLG - Calculate emissions for volatile organic hydrocarbons.
1       HCFLAG - print HC totals, no components
 .067 .065 .072 .074 .072 .068 .062 .056 .046 .033    JULMYR.LDGV..ages 1-10
 .032 .074 .065 .051 .033 .026 .019 .021 .015 .011    .LDGV..my ages 11-20
 .008 .007 .005 .004 .014                             .LDGV..my ages 21-25
 .058 .066 .078 .083 .078 .082 .069 .057 .045 .026    .LDGT1.my ages 1-10
 .024 .065 .068 .040 .031 .024 .015 .019 .015 .012    .LDGT1.my ages 11-20
 .007 .006 .007 .005 .020                             .LDGT1.my ages 21-25
 .058 .066 .078 .083 .078 .082 .069 .057 .045 .026    .LDGT2.my ages 1-10
 .024 .065 .068 .040 .031 .024 .015 .019 .015 .012    .LDGT2.my ages 11-20
 .007 .006 .007 .005 .020                             .LDGT2.my ages 21-25
 .064 .062 .071 .089 .071 .069 .057 .051 .043 .023    .HDGV..my ages 1-10
 .020 .040 .034 .036 .032 .024 .027 .026 .022 .018    .HDGV..my ages 11-20
 .013 .014 .014 .009 .071                             .HDGV..my ages 21-25
 .067 .065 .072 .074 .072 .068 .062 .056 .046 .033    .LDDV..my ages 1-10
 .032 .074 .065 .051 .033 .026 .019 .021 .015 .011    .LDDV..my ages 11-20
 .008 .007 .005 .004 .014                             .LDDV..my ages 21-25
 .058 .066 .078 .083 .078 .082 .069 .057 .045 .026    .LDDT..my ages 1-10
 .024 .065 .068 .040 .031 .024 .015 .019 .015 .012    .LDDT..my ages 11-20
 .007 .006 .007 .005 .020                             .LDDT..my ages 21-25
 .076 .077 .113 .113 .090 .078 .081 .068 .029 .026    .HDDV..my ages 1-10
 .022 .039 .033 .034 .027 .011 .014 .017 .014 .010    .HDDV..my ages 11-20
 .007 .005 .004 .003 .009                             .HDDV..my ages 21-25
 .008 .009 .010 .013 .017 .030 .030 .025 .036 .055    .MC....my ages 1-10
 .037 .730 .000 .000 .000 .000 .000 .000 .000 .000    .MC....my ages 11-20
 0.0  0.0  0.0  0.0  0.0            .MC....my ages 21-25
004
1 7 3 90 90 05.639 00.000
1 7 3 91 97 04.598 00.000
1 7 3 98 03 03.679 00.000
1 7 3 04 50 01.840 00.000
2 1 2 1                          # I/M programs=2,TIER1=no,TTC=yes,RSD=no
82 20 94 98 03 03 097 222 2221 2211 220. 1.20 999.   2500/Idle test
82 20 75 93 03 03 097 222 2221 5211 25.0 25.0 2.00   ASM 2525, phase-in cutpoints
1.00 1.00 1.00 1.00 0.40                 Alternate effectiveness
82 75 98 2221 22 097. 12111111           ATP
82 75 98 2221 22 097.                    Pressure
92 3 81. 81.                             Stage II
bien. t.o. hybrd B  71.  95. 08.5 07.0 92 1 1 1    Local Area Parameter record
4 00 02.5 87.0 20.6 27.3 20.6 01
```

01 2
4 00 05.0 87.0 20.6 27.3 20.6 01
01 2
4 00 10.0 87.0 20.6 27.3 20.6 01
01 2
4 00 15.0 87.0 20.6 27.3 20.6 01
01 2
4 00 19.6 87.0 20.6 27.3 20.6 01 FTP average speed
01 2
4 00 20.0 87.0 20.6 27.3 20.6 01
01 2
4 00 25.0 87.0 20.6 27.3 20.6 01
01 2
4 00 30.0 87.0 20.6 27.3 20.6 01
01 2
4 00 35.0 87.0 20.6 27.3 20.6 01
01 2
4 00 40.0 87.0 20.6 27.3 20.6 01
01 2
4 00 45.0 87.0 20.6 27.3 20.6 01
01 2
4 00 50.0 87.0 20.6 27.3 20.6 01
01 2
4 00 55.0 87.0 20.6 27.3 20.6 01
01 2
4 00 60.0 87.0 20.6 27.3 20.6 01
01 2
4 00 65.0 87.0 20.6 27.3 20.6 01
01 2

APPENDIX C
Data Collection Operating Procedures

HANDBOOK
For
DATA COLLECTORS

Ramp Metering Project

Version One

Georgia Institute of Technology
School of Civil and Environmental Engineering
Spring 1999

TABLE OF CONTENTS

SECTION 1

DAILY OPERTATING PROCEDURE

1. Check Web Site for Cancellations and to Confirm Schedule and Assignment

   - http://transaq.ce.gatech.edu/ramps
   - Weather Cancellations will be Posted by 9:00 AM Each Morning

2. Meet in Room 305 SEB to Checkout Equipment by 2:50 PM

3. Meet in the Parking Lot on the West Side of the SEB for Shuttle to Field Sites

   - Shuttles will Leave at 3:00 PM

4. Setup Equipment and Start Data Collection at 3:15 PM

5. Stop Data Collection at 7:00 PM and Break Down Equipment

6. Wait for Shuttle Pickup by 7:15 PM

   - Do not Leave Site or Leave Equipment Unattended

7. Return to Campus and Check in Equipment

   - Report any Problems
   - Report Time on Time Sheet

SECTION 2

REQUIRED SAFETY CRITERIA

Style of Dress:

All data collectors must wear long pants (i.e. shorts are not acceptable). Each data collector (person) located adjacent to or in the proximity of a road must also wear a safety vest and hard hat. Individuals positioned in moving vehicles are not required to wear the vest and hat while inside the vehicle. The use of headphones or portable radios will not be permitted.

Safety precautions at the Data Collection Site:

1. At no time will a person assigned to collect data enter the active traveled way (the region between edges of road dedicated to vehicle activity).

2. Each person will be dropped-off and picked-up at his or her specific data collection location (unless other arrangements are made with either Dr. Daniel, Dr. Guensler, or Dr. Dixon prior to the day of data collection). When the transportation shuttle delivers individuals to a site, they must exit the shuttle on the side of the vehicle that is not adjacent to traffic. At no time should anyone leave the site without permission from the designated team leader. If an individual needs to leave his or her data collection post for personal reasons, he or she is to contact the team leader via radio or telephone and arrangements will be made for a vehicle to pick-up the person and transport them safely away from the site.

3. Each person should stay alert to errant vehicles. Avoid turning your back completely to traffic.

4. Do not interfere with existing traffic patterns or take any activity (other than those required for the data collection efforts) that may distract drivers or alter driver conditions.

5. Stay as far from the active traveled way as possible.

6. At certain sites, traffic control devices such as parked cars or cones will be positioned to enhance the safety of team members. At no time alter the configuration of these devices.

7. Each data collection site will have data collection zones indicated (generally using surveyor tape or paint). Each person must remain within this zone during the data collection efforts as well as during the intervals before and after collection when the transportation shuttle is not available.

8. If any team member is confronted or threatened during data collection by someone who wants the data collection equipment, do not resist -- surrender the equipment and then immediately report the loss to the team leader and then the police.

Data Collection within a Moving Vehicle:

1. When performing moving data collection studies, allow the driver of the vehicle to collect data only if the activity does not detract from his or her ability to drive.

2. When in a vehicle collecting data in the traffic stream, keep seat belts buckled and do not block the vision of or distract the driver.

SECTION 3

COMMUNICATIONS

Communications between the field workers and the senior staff on the project will be maintained through two-way radios and site visits. One senior staff member will also be equipped with a cellular phone during all data collection secessions. It is encouraged that all data collectors who owen a cellular phone bring it with them to their field locations.

If the need to contact a senior staff member arises, they should be contacted with the two-way radio or a cellular phone directly or have another individual with such capabilities make contact them for you. If you are unable to make communications, wait at your site until a staff member reaches your location. Only leave your location in the case of an emergency.

CELL PHONE CONTACT NUMBER

404.[555].8258

SECTION 4

VEHICEL CLASSIFICATION CODES

1. MOTORCYCLE
2. CARS
3. PICKUPS, VANS, SPORTS UTILITY VEHICLES
4. BUSES
5. 2 AXLE, 6 TIRE SINGLE UNIT TRUCK
6. 3 AXLE SINGLE UNIT TRUCK
7. 4 AXLE SINGLE UNIT TRUCK
8. 4 OR LESS AXLE, DOUBLE
9. AXLE, DOUBLE
10. 6 OR MORE AXLE, DOUBLE
11. 5 OR LESS AXLE, MULTI-UNIT
12. 6 AXLE, MULTI-UNIT
13. 7 OR MORE AKLE, MULTI-UNIT

SECTION 5

LOCATION CODES

Northside Drive		10
Laser Range Finder-Ramp	NSR-LRF	11
Laser Range Finder-Overpass	NSO-LRF	12
Camera	NSO-CAM	13
Howell Mill Road		20
Laser Range Finder-Ramp	HMR-LRF	21
Laser Range Finder-Advanced	HMA-LRF	22
Laser Range Finder-Overpass	HMO-LRF	23
License Plate	HMO-PLT	24
Mores Mill Road		30
Laser Range Finder-Ramp	MMR-LRF	31
Laser Range Finder-Behind	MMB-LRF	32
License Plate	MMO-PLT	33
West Paces Ferry		40
Laser Range Finder-Ramp	WPR-LRF	41
Peachtree Battle		50
Laser Range Finder-Overpass	MLO-LRF	51
License Plate	MLO-PLT	52
Probe Vehicle One (Dodge)		01
Distance Measuring Device One	DMI-1DC	01
Probe Vehicle Two (Ford)		02
Distance Measuring Device Two	DMI-2DC	02

SECTION 6

LASER RANGE FINDER (LRF) GENERAL OPERTIONS

At the data collection site, the following steps should be taken.

1. Setup tripod at specified data collection location--make sure that the tripod is stable.

2. Connect battery handle to LRF.

3. Mount LRFs on surveying tripods with disc and yoke attachment or on a camera tripod directly to battery handle base, before operation. Use of the LRFs in conjunction with the tripods produces the best results.

4. Power on LRF.

5. Test battery and LRF operation, LRFs will default to appropriate RTR mode when powered up. There is no need to adjust the LRF configuration during any portion of this project.

6. Power off LRF.

7. Insert formatted SRAM card with 100 null files (data.000, data.001, etc.) into PCMCIA card slot on gun; remember SRAM cards are inserted upside down when gun is in the off position.

8. Power on LRF.

9. Power on and set JAMAR board (see JAMAR operations).

10. Start data collection:

- For ramp locations track every fourth vehicle. For overpass locations track the fourth vehicle that passes under after your focus has returned back to the HUD.
- Fix LRF cross hairs in heads up display (HUD) on a location on the rear of a vehicle (e.g. the license plate).
- Track vehicle for as long as possible. The LRFs can take reading from distances of over 2000 feet. The distance from the gun to the vehicle will be shown in the HUD. Use these readings as an indication for if the gun is storing readings.
- Keep trigger pulled continuously for each vehicle being tracked.
- Stop distance measurement once a vehicle is out of sight or a fix is lost (i.e. flat line in HUD).

- Record vehicle type on JAMAR board after each trigger pull, manually record vehicle type, LRF P=xxxxxx value and time on JAMAR board on log sheet for approximately every fifth vehicle.

- Before removing the SRAM card, always record the last vehicle tracking on the field log, along with the notation "SRAM card changed" on the next line along with the time from the JAMAR board. After installing the a new SRAM card always record the first vehicle tracked on the field log along with the two digit SRAM card number. For overpass locations also record the lane number for which that data on the card coincides.

13. Avoid squeezing the LRF trigger with the SRAM card installed except when ready to actually collect sample data. Every time the trigger is depressed and released, a separate file on the SRAM card is created. If the trigger is depressed unintentionally, the number of readings (P=xxxxxx) should be recorded on the vehicle log along with the JAMAR board time. A button should be depressed on the JAMAR board as a placeholder for the error file.

12. After approximately half an hour or 60-70 trigger pulls (i.e. vehicles) power off LRF and Remove SRAM card.

- Insert and remove SRAM cards only when LRFs are in the off position.

- Insert SRAM card into PCMCIA card slot (usually the top slot) on the site assigned laptop.

- Down load SRAM card to site assigned laptop using *DOWNLOAD* program. Initiate the program by clicking on the *DOWNLOAD* icon on the laptop. You will be prompted for the location and SRAM card number.

- Insert SRAM card with new null files into the LRF and repeat data collection process (step 10), there is no need to begin a new JAMAR file.

13. Continue until end of data collection period at 7:00 PM.

14. Power off LRF.

15. Remove LRF from tripod and brake down equipment.

CAUTION:

Do not insert or remove SRAM cards when LRF is in the on position.
Do not open the case under any circumstances.
Do not point the LRF directly at the sun.
Do not place the LRF on an unstable surface.
Always transport the LRF in the yellow carrying case.

SECTION 7

JAMAR BOARD GENERAL OPERATIONS

At the data collection site, the following steps should be taken in conjunction with LRF readings.

1. Power on JAMAR board.

2. Make sure that the *FHWA scheme F classification template* is on the board.

3. Start a new count in saturation flow mode (SF) and enter a six digit numeric code (tow digit site ID and four digit date, e.g. *210704* (site twenty-one April seventh)) for the count. JAMAR sequence (COUNT>NEW>SF>8-DIGIT>*sitecode*).

4. The screen will say "Sat Flow Study, Any Key to Start", however when you are ready to start data collection, **button 12 must first be pressed** to start the data collection process.

5. The Board should be located near the LRF, preferably within arms length for quick pressing of button following release of trigger.

6. After release of the trigger on the LRF, immediately press the button on the JAMAR board that corresponds to the type of vehicle tracked.

NOTE: Change the JAMAR board batteries with the provided AA-batteries if a BATT: LOW message is received.

SECTION 8

CAMERA OPETRTIONS

At the data collection site, the following steps should be taken to record the traffic entering the study are on northbound I-75 or at designated intersections.

1. Set up tripod at designated location. Pick a location that will capture the target movements and is free from obstructions.

2. Mount camera on tripod.

3. Connect camera to 8-hour battery pack.

4. Power on camera and insert blank videotape

5. Slide the [CAMERA/VCR] selector to "CAMERA"

6. Slide the [S-VHS ON/AUTO/OFF] selector to "OFF"

7. Remove lens cap.

8. Before recording make sure of the following

- Adjust the field of view so that all traffic lanes are captured on tape--use zoom to adjust.
- Press the [DATE/TIME] button and verify that the correct date and time can be seen in the viewfinder.

9. Press Start/Stop button to initiate recording

10. During the data collection session use the viewfinder to check the following:

- Power supply (a 2-hour back up battery is provided although it should not be needed).
- Field of view (make sure camera has not been moved from original position).
- The camera is in recording mode (i.e. not on pause)

11. Press Start/Stop button to stop recording at 7:00 PM.

12. Disconnect Battery and put camera back in case.

SECTION 9

LICENSE PLATE SURVEY OPERATIONS

At the data collection site, the following steps should be taken. On most days the license plate survey will take place on either the Howell Mill Road overpass or the Mores Mill Road overpass.

1. Locate a position on the overpass above lane one (inside lane)

2. Once your recorder and binoculars are ready start data collection.

3. First record the survey location, date, and start time.

4. Start collecting license plate State and number. Remember to speak clearly and loudly into the recorder microphone.

5. After a plate is recorded, let three vehicles pass and record the license number of the fourth vehicle.

6. Continue this cycle for 15 minutes and then rotate to lane two. Continue to rotate survey from lane to lane every 15 minutes.

7. Change tapes as necessary. Write location and data on tape labels.

8. At 7:00 PM stop collecting license plate numbers.

SECTION 10

PROBE VEHICLE DRIVING AND DATA COLLECTION PROCEDURE

<u>Directions for Driver:</u>

1. After leaving Georgia Tech, drop off data collectors assigned to vehicle for drop-off/pickup at their respective sites in the field. If you do not have passenger proceed to step five (5).
2. After dropping off last passenger, return south via Interstate-75.
3. Travel I-75 south to Exit 102 – 14^{th} and 10^{th} Streets.
4. At 14^{th} Street intersection, turn left and cross I-75, remaining in left lane.
5. Turn left at intersection of Williams Street and 14^{th} Street (immediate next light) and continue onto I-75 Northbound on-ramp.
6. Enter and drive along I-75 as per <u>Car Following Procedure</u>, which follows.
7. Exit the freeway at Exit 108 – Mt. Paran Road and turn left at the light, onto Mt. Paran Road.
8. Turn left at next light (U.S. 41) and return to 14^{th} Street via I-75.
9. Repeat steps 3-9 as many times as possible before 7:00 P.M. On final southbound trip, pickup data collectors assigned to you.

Data Collection:

In order to acquire data with instrumented vehicles, a procedure was developed. This procedure was used in the collection of all data using instrumented vehicles. It was adapted from the procedures Sierra Research, Inc. developed in its work (Austin, DiGenova, et al. 1993).

Car Following Procedure:

1. Enter the freeway.
2. Driver spots the first white vehicle downstream (in front) of him/her, and enters the lane in which that vehicle is found (when it is safe to do so). Once in the lane, the vehicle immediately in front of the driver is the target vehicle. Driver indicates which vehicle is the target vehicle to the instrument person(s).
3. Follow the target vehicle and mimic its behavior as best as possible, while maintaining a **safe** distance from the vehicle (headway). This means the driver brakes when it brakes, changes lanes when it changes lanes, speeds up when it speeds up, and maintains the speed at which it travels, including above the speed limit (vehicles should not exceed the general flow of traffic).
4. A target vehicle must be acquired before the beginning mark for the run (a designated roadside sign) is reached. A target vehicle must be tracked through the run until the ending sign is reached.

Target Vehicles: The target vehicle is the vehicle that the instrumented vehicle is following. The instrumented vehicle is trying to capture the speed and acceleration activity of the target vehicle.

Following Above Speed Limit: Target vehicles can travel above the speed limit. On some facilities it is quite common. If runs are aborted because the target vehicle goes above the speed limit, the data sample will be biased due to the lack of vehicles in the sample which travel above the speed limit. Permissions must be obtained from the appropriate regulatory authorities to exceed speed limits for purposes of data collection. For this project, since permission has not been obtained, vehicles shall not exceed speeds above the general flow of traffic.

Changing the Target Vehicle: Each selected target is followed as long as reasonably possible. If a target cannot be followed safely through a lane or speed change, a new target is chosen.

a. If a vehicle gets between driver and the target vehicle, the vehicle immediately in front of the driver becomes the [new] target vehicle. If no vehicle is immediately in front of the driver, a new target vehicle will be acquired using the same procedure used to acquire the initial target.

b. If a vehicle changes lanes in busy traffic [or some other erratic maneuver] and cannot be followed, the driver will duplicate the maneuver safely as soon as possible. Once the maneuver is complete and the driver is in the new lane, the vehicle immediately in front of the driver becomes the [new] target vehicle.
c. If a vehicle exits or obviously is going to exit, a new target is selected. The vehicle immediately in front of the driver becomes the [new] target vehicle.
d. If a target vehicle is changed during a run, the change and the point at which it occurs should be noted in the vehicle log. The distance from the start of the run to the location of the change should be noted in the vehicle log by pressing the DISP/HOLD button on the NS-60 and recording the number.

<u>Instrumented Car Travel at Other Times</u>: At all times when the instrumented car is not following a target (e.g., while trying to acquire a new target in busy traffic), the instrumented car will match the general flow of through traffic around it.

Directions for DMI Operator:

The DMI (distance measurement instrument) operator will ride along in probe vehicle and run the Nitestar NS-60 device as well as the laptop used for downloading of data while the driver completes a prescribed circuit on I-75. The procedure to be used follows:

1. Setup computer while driver drops off passengers and returns to start of course (14th/Williams St. on-ramp).
    a. Plug adapter into serial port of laptop computer and connect computer to the NS-60 with provided cable.
    b. Turn on computer and NS-60. Allow computer to boot up.
    c. Open Windows Explorer and open the **DMI** directory.
2. Make sure the NS-60 is in **COUNT HOLD** mode, and units in feet.
3. Run a test of the data collection program to verify that data is being transferred to the laptop.
    a. Run the application entitled **Qbasic**, which will open a DOS window.
    b. Press **Esc** or click on <escape> to start program.
    c. Press **Alt-F**, then **O**, to open a file. Select **DMIRUN.BAS** and press **Enter.**
    d. Press **Shift-F5** to begin collecting data from the NS-60. The display on the laptop should be a string of timestamps with three columns of zeros.
    e. Press **RUN/HOLD** on the NS-60 to begin counting. The display should begin counting with columns for timestamp, distance travelled, delta distance, and speed.
    f. Press **RUN/HOLD** to stop counting.
    g. Press **Ctrl-Break** on the laptop to close the data window.
    h. Press **Alt-F**, then **X,** to exit the DOS window
    i. Press **CLEAR** to clear memory of the NS-60.
    j. Open the file **testout.dat** with a word processor to verify that data was written during the previous steps. If not, check connections and or reboot, then repeat steps 3a through 3i until data is written to the test file.
    k. Close data file.
4. When driver re-enters freeway at Williams St., be prepared to begin counting.
5. Repeat steps 3a-3d and collect a few seconds of blank test data to delineate "real" distance data.
6. Press **RUN/HOLD** exactly when the vehicle passes the Northside Drive exit sign to begin collecting "real" data. Try not to disturb the device while collection is in progress.
7. Target vehicles should be identified before reaching Northside Drive sign. Record vehicle information for each run on the log sheet.

8. If the target vehicle is changed during the run the new vehicle should be noted in the log along with the distance from the beginning of the run at which the change occurred. The distance from the beginning of the run can be noted by pressing **DISP/HOLD** on the NS-60. Pressing **DISP/HOLD** again sets the counter to the current distance.
9. Press **RUN/HOLD** exactly when the vehicle passes the second mark at Mt Paran Road ½ mile exit sign.
10. Repeat steps 3g-3i.
11. While driver is returning to 14th Street, verify that data was written to the file **testout.dat**.
12. Rename the file **testout.dat** using the following naming scheme:
    Filename = ***VMMDDRR.dmi,*** where ***V*** is the vehicle designation (1 or 2), ***MM*** is the two digit month designation, ***DD*** is the two digit day designation, and ***RR*** is the two digit number of the run just performed (i.e., the first run of the day is 01).
13. Fill out log sheets for each run.
14. Repeat steps 4-13 until approximately 7:00 P.M.
15. Return to campus after picking up any passenger that were dropped off at the beginning of the session.

APPENDIX D
Simulation Model Input Data

Table D-1
Observed Flow Entry Node Simulation Data
Start Time: 3:45 p.m.
Observed Freeway and Arterial Volumes
(Note: volumes for metered versus non-metered are similar)

	Time (minutes)	Northside NB Veh	Northside SB veh	Howell Mill NB veh	Howell Mill SB veh	Moores Mill EB veh	Moores Mill WB veh	Paces Ferry NB veh	Paces Ferry SB veh	Freeway I-75 NB veh
Time Period #1	0	31	53	26	42	20	30	30	30	391
	5	47	46	24	40	14	29	30	30	401
	10	28	58	26	35	17	35	30	30	416
	15	36	50	25	41	22	30	30	30	393
	20	43	47	34	43	17	29	30	30	376
	25	38	50	14	53	28	28	30	30	354
	30	41	45	17	41	23	28	30	30	397
	35	47	56	30	49	17	29	30	29	377
	40	48	50	37	27	16	35	30	30	407
	45	50	51	37	34	19	25	30	26	390
	50	41	43	31	35	21	29	30	32	344
	55	55	51	23	39	22	26	30	30	388
	60	59	56	34	48	23	28	30	33	379
	65	58	57	27	40	21	26	30	29	428
	70	62	41	27	60	20	36	30	33	403
Time Period #2	75	60	34	24	29	23	32	48	27	417
	80	57	50	31	38	20	34	47	25	358
	85	71	46	26	40	26	30	44	22	362
	90	70	46	31	52	20	32	42	24	391
	95	71	52	34	32	30	32	60	35	416
	100	72	44	22	54	19	22	46	30	431
	105	65	49	40	38	21	20	46	28	386
	110	68	53	32	37	26	26	42	41	313
	115	62	46	39	41	26	32	40	26	316
	120	68	40	34	50	20	22	43	22	308
	125	78	36	36	37	19	23	55	28	368
	130	59	41	43	35	24	23	32	17	419
	135	67	39	33	46	23	24	38	38	421
	140	71	34	40	36	30	29	40	24	386
	145	65	40	23	42	15	26	31	17	401
Time Period #3	150	61	47	31	36	19	17	30	16	389
	155	56	32	44	43	23	17	30	16	385
	160	55	48	32	36	25	16	30	16	380
	165	73	38	32	32	15	19	30	16	371
	Total	1,934	1,570	1,039	1,382	724	920	1,225	921	13,065

Table D-2
High Flow Entry Node Simulation Data
Start Time: 3:45 p.m.
Maximized Freeway Volumes (arterial volumes assumed similar to observed flows)
(Note: volumes for metered versus non-metered are similar)

	Time (minutes)	Northside NB Veh	Northside SB veh	Howell Mill NB veh	Howell Mill SB Veh	Moores Mill EB veh	Moores Mill WB veh	Paces Ferry NB veh	Paces Ferry SB veh	Freeway I-75 NB veh
Time Period #1	0	31	53	26	42	20	30	30	30	500
	5	47	46	24	40	14	29	30	30	500
	10	28	58	26	35	17	35	30	30	500
	15	36	50	25	41	22	30	30	30	500
	20	43	47	34	43	17	29	30	30	500
	25	38	50	14	53	28	28	30	30	500
	30	41	45	17	41	23	28	30	30	500
	35	47	56	30	49	17	29	30	29	500
	40	48	50	37	27	16	35	30	30	500
	45	50	51	37	34	19	25	30	26	500
	50	41	43	31	35	21	29	30	32	500
	55	55	51	23	39	22	26	30	30	500
	60	59	56	34	48	23	28	30	33	500
	65	58	57	27	40	21	26	30	29	500
	70	62	41	27	60	20	36	30	33	500
Time Period #2	75	60	34	24	29	23	32	48	27	500
	80	57	50	31	38	20	34	47	25	500
	85	71	46	26	40	26	30	44	22	500
	90	70	46	31	52	20	32	42	24	500
	95	71	52	34	32	30	32	60	35	500
	100	72	44	22	54	19	22	46	30	500
	105	65	49	40	38	21	20	46	28	500
	110	68	53	32	37	26	26	42	41	500
	115	62	46	39	41	26	32	40	26	500
	120	68	40	34	50	20	22	43	22	500
	125	78	36	36	37	19	23	55	28	500
	130	59	41	43	35	24	23	32	17	500
	135	67	39	33	46	23	24	38	38	500
	140	71	34	40	36	30	29	40	24	500
	145	65	40	23	42	15	26	31	17	500
Time Period #3	150	61	47	31	36	19	17	30	16	500
	155	56	32	44	43	23	17	30	16	500
	160	55	48	32	36	25	16	30	16	500
	165	73	38	32	32	15	19	30	16	500
	Total	1,934	1,570	1,039	1,382	724	920	1,225	921	16,998

Table D-3
Observed Flow Lane Closure Simulation
Entry Node Simulation Data
Start Time: 5:00 p.m.
(Note: volumes for metered versus non-metered are similar)

	Time (minutes)	Northside NB Veh	Northside SB veh	Howell Mill NB veh	Howell Mill SB Veh	Moores Mill EB veh	Moores Mill WB veh	Paces Ferry NB veh	Paces Ferry SB veh	Freeway I-75 NB veh
Time Period #1	0	60	34	24	29	23	32	48	27	417
	5	57	50	31	38	20	34	47	25	358
	10	71	46	26	40	26	30	44	22	362
	15	70	46	31	52	20	32	42	24	391
	20	71	52	34	32	30	32	60	35	416
	25	72	44	22	54	19	22	46	30	431
	30	65	49	40	38	21	20	46	28	386
	35	68	53	32	37	26	26	42	41	313
	40	62	46	39	41	26	32	40	26	316
	45	68	40	34	50	20	22	43	22	308
	50	78	36	36	37	19	23	55	28	368
	55	59	41	43	35	24	23	32	17	419
	Total	802	537	392	482	275	328	545	325	4,486

Table D-4
High Flow Flow Lane Closure Simulation
Entry Node Simulation Data
Start Time: 5:00 p.m.
(Note: volumes for metered versus non-metered are similar)

	Time (minutes)	Northside NB Veh	Northside SB veh	Howell Mill NB veh	Howell Mill SB Veh	Moores Mill EB veh	Moores Mill WB veh	Paces Ferry NB veh	Paces Ferry SB veh	Freeway I-75 NB veh
Time Period #1	0	60	34	24	29	23	32	48	27	500
	5	57	50	31	38	20	34	47	25	500
	10	71	46	26	40	26	30	44	22	500
	15	70	46	31	52	20	32	42	24	500
	20	71	52	34	32	30	32	60	35	500
	25	72	44	22	54	19	22	46	30	500
	30	65	49	40	38	21	20	46	28	500
	35	68	53	32	37	26	26	42	41	500
	40	62	46	39	41	26	32	40	26	500
	45	68	40	34	50	20	22	43	22	500
	50	78	36	36	37	19	23	55	28	500
	55	59	41	43	35	24	23	32	17	500
	Total	802	537	392	482	275	328	545	325	5,999

APPENDIX E
ACRONYMS

ATMS: Advanced Traffic Management System

CAAA: Clean Air Act Amendments

CARB: California Air Resource Board

CFR: Code of Federal Regulations

CMAQ: Congestion Mitigation and Air Quality Program

CO: Carbon Monoxide

CO_2: Carbon Dioxide

DMI: Distance Measuring Instrument

EGR: Exhaust Gas Recirculation

FHWA: Federal Highway Administration

FTP: Federal Test Procedure

GDOT: Georgia Department of Transportation

GIS: Geographic Information System

HC: Hydrocarbons

HONO: Nitric Acid

HUD: Heads-Up Display

IPS: Inertial Power Surrogate

ISTEA: The Intermodal Surface Transportation Efficiency Act of 1991

ITE: Institute of Transportation Engineers

ITS: Intelligent Transportation Systems

JASPROD: Joint Acceleration-Speed Probability Density Function

LDV: Light Duty Vehicle

LOS: Level of Service

LRF: Laser Rangefinders

MEASURE: Mobile Emission Assessment System for Urban and Regional Evaluation

MPO: Metropolitan Planning Organization

NAAQS: National Ambient Air Quality Standards

NCHRP: National Cooperative Highway Research Program

NMHC: Non-Methane Hydrocarbon

NO: Nitrogen Oxide

NOx: Oxides of Nitrogen

NO_2: Nitrogen Dioxide

O_3: Ozone

OH: Hydroxyl Radical

PARCLO: Partial Cloverleaf

PM: Particulate Matter

PPM: Parts Per Million

Pb: Lead

ROG: Reactive Organic Gas

SCAQMD: South Coast Air Quality Management District

SI: Spark Ignition

SIP: State Implementation Plan

SOx: Oxides of Sulfur

SUV: Sports Utility Vehicle

TCM: Transportation Control Measure

TEA-21: Transportation Equity Act for the 21st Century

TMC: Traffic Management Center

TTI: Texas Transportation Institute

USDOT: United States Department of Transportation

USEPA: United States Environmental Protection Agency

VOC: Volatile Organic Compounds

VIN: Vehicle Identification Number

VMT: Vehicle Miles Traveled

V/C: Volume to Capacity Ratio